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Interrelationships among water, air, and chemical transport properties of soil

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Interrelationships among water, air, and chemical

transport properties of soil

by

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GENERAL INTRODUCTION

The impact of agricultural activities on surface and groundwater quality has been a source of much debates in the recent years. Fertilizer and other agricultural chemicals are being used in increasing quantities as the demand for higher soil productivity increases (Tisdale and Nelson, 1975). Agriculture is considered to be a large contributer to the non-point sources of groundwater contamination. If groundwater is to continue to play an important role in the development of the world's water resource potential, then it will have to be protected from the increasing threat of subsurface contamination. Groundwater monitoring and sampling programs in the United States have resulted in an increasing awareness of nitrate levels and presence of pesticides in the groundwater resulting from agricultural practices (Fairchild, 1987; Hallberg et al., 1985; Kelly, 1985).

Agricultural and environmental concerns often require knowledge of flow parameters in unsaturated and saturated soils, notably, hydraulic conductivities. Variability in these parameters within a given soil series or within very small field areas occurs as a result to the complexity of parant material, development factors and management factors (Schuh et al., 1984).

In central Iowa, soil was formed predominately as glacial till deposited by the Late Wisconsinan Des Moines Lobe (Kemmis et al., 1981; Anderson, 1983). The Wisconsinan age till contains two distinct weathering zones; an upper mottled, unleached, oxidized or reduced zone and a lower unleached, unoxidized zone (Kemmis et al., 1981).

The weathered till is a region of active groundwater flow; however, the magnitude and directions of groundwater flow are often uncertain (Ruland et al., 1991).

The benefits of adopting conservation tillage have historically focused on decreased soil erosion and decreased sediment and contaminant delivery to surface water (Baker, 1987). In recent years, however, increased emphasis has been devoted to evaluating the impacts of conservation tillage on groundwater quality.

While it is well recognized that conservation tillage reduces both wind and water erosion (Lindstrom et al., 1979; Campbell et al., 1979; Skidmore et al., 1979; Voorhees et al., 1979), the impact of conservation tillage on the physical and hydraulic properties of soil has been highly inconsistent (Bauder et al., 1981; Hill and Cruse, 1985; Horton et al., 1989; Wagger and Denton, 1989).

The ability of soils to retain and transmit water is influenced by the hydraulic properties of the soil. These properties are determined by the geometry of the pore space (Klute, 1982). Tillage and compaction can alter pore geometry and consequently affect water retention and transport properties. Volumetric water content has been found to be consistently greater in soils maintained under conservation tillage systems than those under conventional tillage systems (Gantzer and Blake, 1978; Lindstrom et al., 1984).

The effects of tillage on saturated hydraulic conductivity, K_{sat}, have also been highly inconsistent. Culley et al. (1987) found that the values of K_{sat} under no-tillage exceeded those under conventional tillage despite the soil's higher bulk density, lower total porosity and greater soil strength. They suggested that macropores may be the mechanism responsible for the greater permeability. Other researchers, however, found that the values of K_{sat} with no-tillage were either lower (Heard et al., 1988) or did not differ from those under conventional tillage (Obi and Nnabude, 1988).

Use of conservation tillage typically results in an increased infiltration rate of water, decreased water evaporation and decreased surface runoff (Beven and Germann, 1982; Wagnent, 1987). Differences in infiltration and hydraulic conductivity in soils managed under no-tillage have been attributed to movement of water through large, surface-connected, continuous pores in the soil (Ehlers, 1975; Hall et al., 1987; Edwards et al., 1988) These large connected pores can conduct large amounts of water under both saturated and unsaturated conditions (Moore et al., 1986; Watson and Luxmoore, 1986). Because macropores typically occupy only a small fraction of the total soil volume, the water and dissolved chemicals may bypass the vast majority of soil water held in the biologically active surface horizons, increasing the possibility of groundwater contamination (Beven and Germann, 1982; Dick et al., 1989).

Air permeability has been used in attempts to characterize soil pore geometry (Ball, 1981,a,b; Groenevelt and Lemoine, 1987). Bear (1972) revealed that pore-geometric factors strongly influence soil air flow. These geometric factors include total porosity, pore size distribution, pore continuity, tortuousity, and pore shape. Evaluation of air permeability and penetrability may provide a measure of the structural degradation of soil due to intensive cultivation (Ball, 1981b). Roseberg and McCoy (1992) suggested that air permeability measurement and data analysis techniques afford the opportunity for more quantitative description of changes in soil macroporosity and macropore continuity due to management.

Literature describing the effects of tillage on unsaturated hydraulic conductivity is very limited. Negi et al. (1981) found that at the same volumetric water content, the unsaturated hydraulic conductivity of tilled soils was higher than for non-tilled soils.

Because of the difficulties associated with the direct measurement of unsaturated hydraulic conductivity, many investigators have searched for alternative ways to estimate it. Numerous methods have been proposed to estimate hydraulic conductivity indirectly from more easily measured soil properties. Attempts have been made to estimate hydraulic properties of soil by using data such as soil texture, organic matter content, and bulk density. Clapp and Hornberger (1978) have estimated the exponent of a power function model for soil water retention by using soil textural information. Bloemen (1980) used textural properties to estimate parameters in the Brooks and Corey (1964) equation. Schuh and Bauder (1986) indicated that bulk density was not always a productive indicator of unsaturated hydraulic conductivity because of ambiguity resulting from both grain size and compaction. They have also shown that organic matter content correlated with hydraulic conductivity only at high water contents.

Much attention has been devoted to the use of pore size distribution functions obtained from soil water retention curves for predicting hydraulic conductivity. Among the most popular methods have been Millington and Quirk (1961), Brooks and Corey (1964), Campbell (1974) and more recently van Genuchten (1978 and 1980).

Air and water are two fluids occupying similar pore spaces in the soil. Flow properties of these two fluids are interrelated, and, therefore, it is conceptually possible to estimate the hydraulic conductivity of one fluid from knowledge of the other.

This study was focused on obtaining a more complete understanding of soil hydraulic properties. First paper of this study describes laboratory measures of chloride movement and saturated hydraulic conductivity for glacial till soil samples. Second paper of this study presents tillage and traffic effects on soil bulk density, saturated hydraulic conductivity, chloride breakthrough curves, air permeability and unsaturated hydraulic conductivity. Thrid paper of this study presents an analysis of a method and estimating the unsaturated hydraulic conductivity from air permeability measurements.

Explanation of Dissertation Format

This study is presented in three papers. Each section was written as a complete article in a format acceptable for publication in a refereed scientific journal. The first paper, "Determination of Saturated Hydraulic Conductivity and Dispersivity for Glacial Till Deposit samples", will be submitted for publication in the Ground

Water journal. The second paper, "Effects of Two Tillage Systems and Traffic on Water Retention and Transport of Water, Chemical and Air in the Soil", will be submitted for publication in the soil and water management and conservation division of the Soil Science Society of America Journal. The third paper, "Predicting Unsaturated Hydraulic Conductivity from Air Permeability", will also be submitted to the Soil Science Society of America Journal. Following these three papers is a General Summary of the results and conclusions of the three studies. Literature cited in this General Introduction and in the General Summary is listed under Additional References.

PAPER I. DETERMINATION OF SATURATED HYDRAULIC CONDUCTIVITY AND DISPERSIVITY FOR GLACIAL TILL DEPOSIT SAMPLES

ABSTRACT

Thin-wall Shelby tubes were used to collect undisturbed soil samples from depths of 2-12 m from several glacial till profiles. Saturated hydraulic conductivity and chloride breakthrough measurements were made either directly on soil within Shelby tubes or on soil samples removed from the Shelby tubes and then sealed into aluminum rings with paraffin wax.

Visual observation indicated the presence of oxidized till of 3 m thickness underlain by unoxidized till. Bulk density, particle density, specific surface, and particle size analysis indicated little or no change among the samples. Saturated conductivity, K_{sat}, decreased significantly with depth. Below a 9 m depth, however, the conductivity remained nearly unchanged.

The K_{sat} values determined on the samples contained within Shelby tubes were one order of magnitude higher than those determined on the same samples removed from Shelby tubes and sealed into aluminum rings. Dispersivity values were significantly higher for samples contained within Shelby tubes than for the same samples removed from Shelby tubes and sealed into rings. The high conductivity, dispersivity, and early chloride breakthroughs for samples contained within Shelby tubes all indicated side-wall flow. The lower conductivity, dispersivity, and delayed chloride breakthrough all indicated that wax sealing of soil samples prevented side-wall flow.

INTRODUCTION

The demands for greater agricultural yields in the United States until about the 1900s were met primarily by bringing new land into cultivation. Recently, substantial improvement in agricultural production has come from larger yields on land already in cultivation. As the demand for higher productivity increases more and more, fertilizers and other agricultural chemicals are being used (Tisdale and Nelson, 1975).

Agriculture is considered to be a large contributor to the non-point sources of groundwater contamination. According to the Statistical Abstract of the United States compiled by the U.S. Bureau of Census (1989; cited by Moody, 1990), about 330 million acres were used for crop production in the United States in 1987, which was the largest areal extent among human activities related to the contamination of groundwater.

If groundwater is to continue to play an important role in the development of the world's water resource potential, then it will have to be protected from the increasing threat of subsurface contamination. Groundwater monitoring and sampling programs in the United States have resulted in an increasing awareness of nitrate levels and presence of pesticides in the groundwater resulting from agricultural practices (Fairchild, 1987; Hallberg et al., 1985; Kelly, 1985). Nearly 50% of the nation's drinking water supply comes from groundwater, and about 95% of all rural households rely on groundwater for their drinking water (CAST, 1985).

A large portion of the present land forms in the northern United States are the results of continental glaciation (Barari and Hedges, 1985). Much of central Iowa is occupied by soil materials formed predominately in glacial till deposited by the Late Wisconsinan Des Moines Lobe (Kemmis et al., 1981; Anderson, 1983). The Wisconsinan age till contains two distinct weathering zones; an upper mottled, unleached, oxidized or reduced zone and a lower unleached, unoxidized zone (Kemmis et al., 1981). The weathered till is a region of active groundwater flow; however, the magnitudes and directions of groundwater flow are often uncertain (Ruland et al., 1991).

Few studies have been performed to characterize the hydraulic properties of the Wisconsinan Des Moines Lobe. Among these is that of Jones et al. (1992). They reported that the hydraulic conductivity estimates for Wisconsinan age weathered till in Iowa were 1 to 3 orders of magnitude higher than values for weathered till reported in the literature for different states. They also reported that the high conductivity may result in part from differences in parent materials.

Since in situ measurements of the hydraulic conductivity are difficult and sometimes impossible in tills (Jones et al., 1992), laboratory measurements become very important in order to estimate the hydraulic conductivity. Laboratory measurements of weathered till, however, have often resulted in lower values of the hydraulic conductivity than field measurements (Lutenegger et al., 1983).

The main objective of this study was to measure the hydraulic conductivity and solute breakthrough in the laboratory. Another objective was to compare conductivity obtained from samples contained in Shelby tubes with conductivity determined on soil samples removed from Shelby tubes and then sealed into aluminum rings.

MATERIALS AND METHODS

Thin-wall Shelby tubes were used to collect undisturbed soil samples from depths of 2-12 m, from several glacial till profiles at the Iowa State University Agronomy Farm, west of Ames.

These samples were used to measure saturated hydraulic conductivity and chloride breakthrough. Measurements were performed either directly on soil within Shelby tubes after cutting the tubes to about 15 cm in length or on soil samples extruded from the Shelby tubes. Soil samples were removed from tubes by using a manual-piston jacking system. Once removed, soil was trimmed to a uniform cylindrical shape, and the side walls were then coated with a layer of paraffin wax. Each sample was then placed in a 7.6 x 7.6 cm aluminum ring and the gap was filled with paraffin wax at 65° C in an incremental manner, 1.0 cm increment at a time until the top rim of the sample was reached. Paraffin was allowed to solidify between increments. The paraffin wax was painted on to prevent wax penetration into the soil sample while the gap was filled.

Hydraulic conductivity was measured by using a fixed-wall permeameter (Klute and Dirksen, 1986). A 0.01 N $CaSO_4$ solution at 10 psi pressure was used to saturate the samples. After a steady flow rate was established, saturated hydraulic conductivity, K_{sat}, was measured and a steady flow miscible displacement experiment was conducted using a 0.05 N $CaCl_2$ solution to displace the $CaSO_4$ solution.

In the miscible displacement experiment, effluent exiting the lower boundary was collected in fractions at equal-time increments.

Chloride concentration was determined by using constant potential coulometric automatic titration (Adriano and Doner, 1982).

An equation for longitudinal dispersion of a solute within a steady state flow through a homogeneous porous medium is (Kirkham and Powers, 1984)

$$\frac{\partial c}{\partial t} = D \frac{\partial^2 c}{\partial x^2} - v \frac{\partial c}{\partial x} \tag{1}$$

where c is the solute concentration (ML^{-3}), x is the spatial dimension of the soil sample (L), t is time (T), D is the hydrodynamic dispersion coefficient (L^2T^{-1}), and v is the average pore-water velocity (LT^{-1}). Dispersivity, α, being a characteristic property of the porous medium is estimated using the following equation (Parker and van Genuchten, 1984)

$$\alpha = \frac{D}{v} \tag{2}$$

where $D = D_s + D_h$. D_s is the diffusion coefficient, and D_h is the dispersion coefficient (Hillel, 1980). Equation (1) assumes that the displacing and displaced miscible fluids are of the same density and viscosity and that the solute does not interact with the soil.

When subject to the boundary and initial conditions

$$\begin{aligned} &c(x,0) = c_i \\ &c(0,t) = c_0 \ ; \qquad 0 < t \leq t_0 \\ &\frac{\partial c}{\partial x}(\infty,t) = 0 \end{aligned} \tag{3}$$

the solution of (1) is (Lapidus and Amundson, 1952)

$$c(x,t) = c_i + (c_0 - c_i)\,A(x,t); \qquad 0 < t \le t_0 \tag{4}$$

where

$$A(x,t) = \frac{1}{2}\,\mathrm{erfc}\left[\frac{x - vt}{2(Dt)^{1/2}}\right] + \frac{1}{2}\exp(vx/D)\,\mathrm{erfc}\left[\frac{x + vt}{2(Dt)^{1/2}}\right] \tag{5}$$

Dimensionless time and concentration variables were used to express the results of the steady fluid flow miscible displacement experiments. The dimensionless time variable, T, is defined by $T = vt/L$ in which, L, is the length of the soil sample. The dimensionless concentration c is

defined by $c = (c - c_i)/(c_0 - c_i)$.

Equation (4) was fitted to the breakthrough curve data by using a non-linear least squares inversion method (Parker and van Genuchten, 1984), to determine D in equation (1).

Bulk density was determined on selected fragments of 60 to 80 cm^3 by using a clod method described by Blake and Hartge (1986). Particle density was determined with a pycnometer, according to Blake (1965). Specific surfaces were determined according to Carter et al. (1986). Particle size distribution was determined by the pipette method according to Walter et al. (1978).

Statistical analysis of the data was conducted using analysis of variance procedures (SAS Institute, Inc., 1985).

RESULTS AND DISCUSSIONS

Table 1 presents a summary of the sampling depths, oxidization conditions, bulk densities, particle densities, and specific surfaces of the soil samples used in this study. The Wisconsinan age till contains a weathered (oxidized) zone of 3 to 5 m thickness underlain by unweathered till (Anderson, 1983). Our data showed that the till at the study site contained an oxidized till zone of 3 m thickness underlain by an unoxidized till zone.

Bulk densities of the soil samples ranged from 1.84 to 2.00 Mg m^{-3}, and they increased with depth. This increase in bulk density was significant ($P \leq 0.05$). Particle density, and specific surface varied little with depth. Particle density and specific surface ranged from 2.67 to 2.68 Mgm^{-3} and from 42 to 52 m^2g^{-1}, respectively. The variations in particle density and specific surface values with depth were not significant ($P \leq 0.05$). Textural analysis indicated that samples did not differ significantly ($P \leq 0.05$). Clay content ranged between 15.8% to 16.4% (Table 2). Silt and sand content ranged between 34.2% to 35.3% and between 48.5% to 49.4%, respectively. These samples were classified as silt loam materials according to the USDA textural classification.

Figure 1 shows a typical particle-size distribution curve for the soil materials used in this study. This data is similar to those presented by Kemmis (1981) and Wang (1990), for comparable tills.

Average saturated hydraulic conductivity, K_{sat}, and the apparent dispersivity, α, for the samples removed from Shelby tubes are

Table 1. Summary of the sampling depths, oxidization conditions, bulk density, ρ_b, particle density, ρ_s, specific surface, SS, and standard deviation, SD, of the soil materials studied

Depth (m)	Till condition	ρ_b	(SD)	ρ_s	(SD)	SS	(SD)
		Mg m^{-3}				$m^2 g^{-1}$	
2-3	oxidized	1.84	0.03	2.68	0.01	52	18
2-5	unoxidized	1.97	0.05	2.68	0.01	45	6
5-8	unoxidized	1.97	0.04	2.67	0.01	42	5
8-12	unoxidized	2.00	0.03	2.68	0.01	44	4

Table 2. Particle size fractions and standard deviation , SD, of the soil samples used in this study

Depth (m)	Sand	(SD)	Silt	(SD)	Clay	(SD)
			%			
2-3	49.4	0.29	34.2	0.32	16.4	0.50
2-5	48.9	0.38	35.2	0.55	15.9	0.63
5-8	49.4	2.21	34.8	1.54	15.8	0.74
8-12	48.5	0.50	35.3	0.56	16.2	0.19

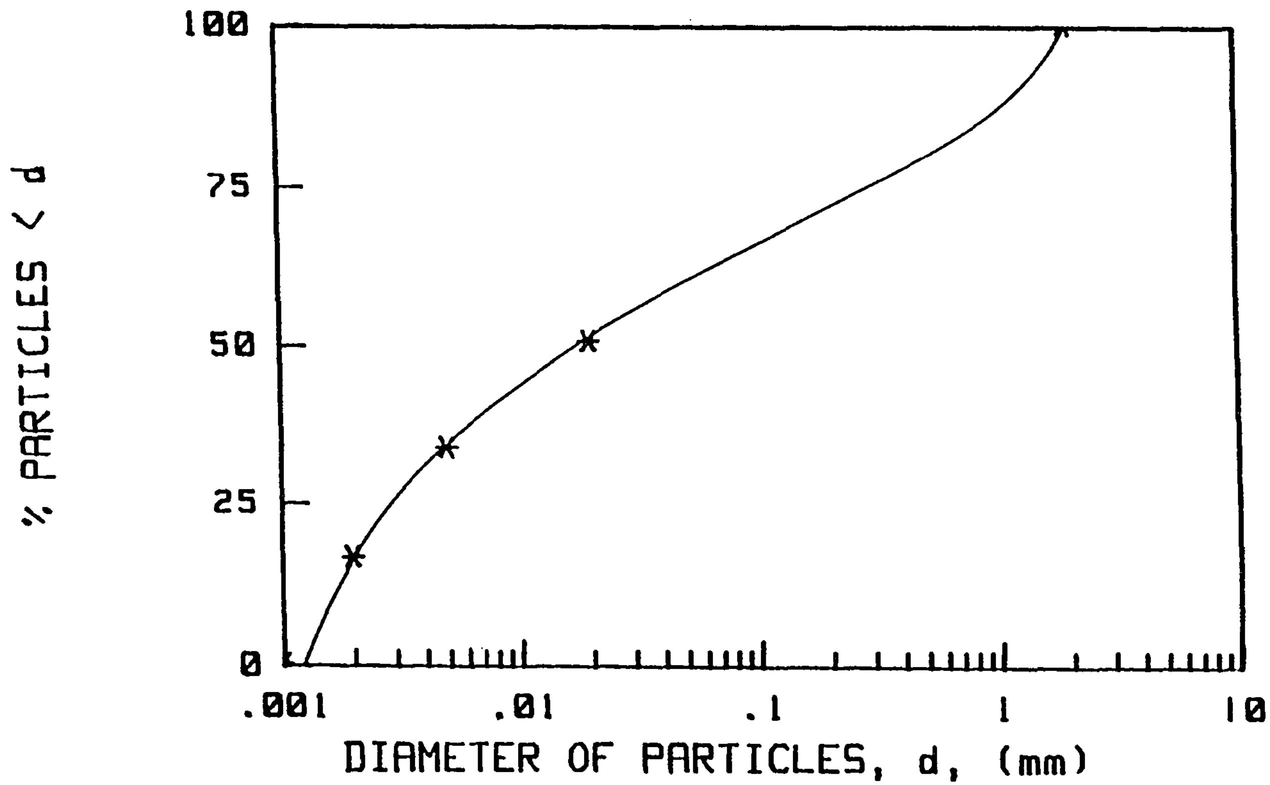

Figure 1. A typical particle-size distribution curve for the soil material used in this study

presented in Table 3. The results indicated a significant ($P \leq 0.05$) decrease in K_{sat} with depth. This should be expected as results of a decrease in weathering and greater confining stress (Lutenegger, 1990). In contrast, dispersivity increased slightly with depth indicating the presence of relatively larger pores in the deeper samples. Methylene blue dye confirmed this finding visually. This increase, however, was not significant ($P \leq 0.05$). The variation of the hydraulic conductivity with depth is shown in Fig. 2 for all the samples. Conductivity decreased with depth passing from the upper oxidized materials into the unoxidized lower zone. Below a depth of about 9 m, the conductivity is nearly unchanged with depth. This finding was similar to that of Lutenegger (1989).

Table 4 presents a comparison between two determinations of K_{sat} and α for two samples. One determination was conducted when the soil samples were in the Shelby tubes and a second determination was conducted after removing the soil samples from Shelby tubes. The results showed that saturated hydraulic conductivity was nearly one order of magnitude higher when determined on soil inside the Shelby tubes as compared with saturated conductivity determined on the same samples after being removed from the Shelby tubes and sealed into aluminum rings. Dispersivity, α, which is a characteristic property of the porous medium was also significantly higher for the samples contained within the Shelby tubes than for samples removed from the Shelby tubes. Higher dispersivity indicates possible flow occuring

Table 3. Measured saturated hydraulic conductivity, K_{sat}, dispersivity, α, and standard deviation obtained from samples removed from Shelby tubes and sealed with paraffin wax into aluminum rings

Depth (m)	K_{sat}	(SD)	α	(SD)
	cm s^{-1}		cm	
2-3	1.85×10^{-6}	1.95×10^{-6}	1.64	0.82
2-5	3.26×10^{-7}	1.42×10^{-7}	1.98	2.17
5-8	2.41×10^{-7}	1.40×10^{-7}	2.01	1.69
8-12	1.64×10^{-7}	5.35×10^{-8}	2.57	2.26

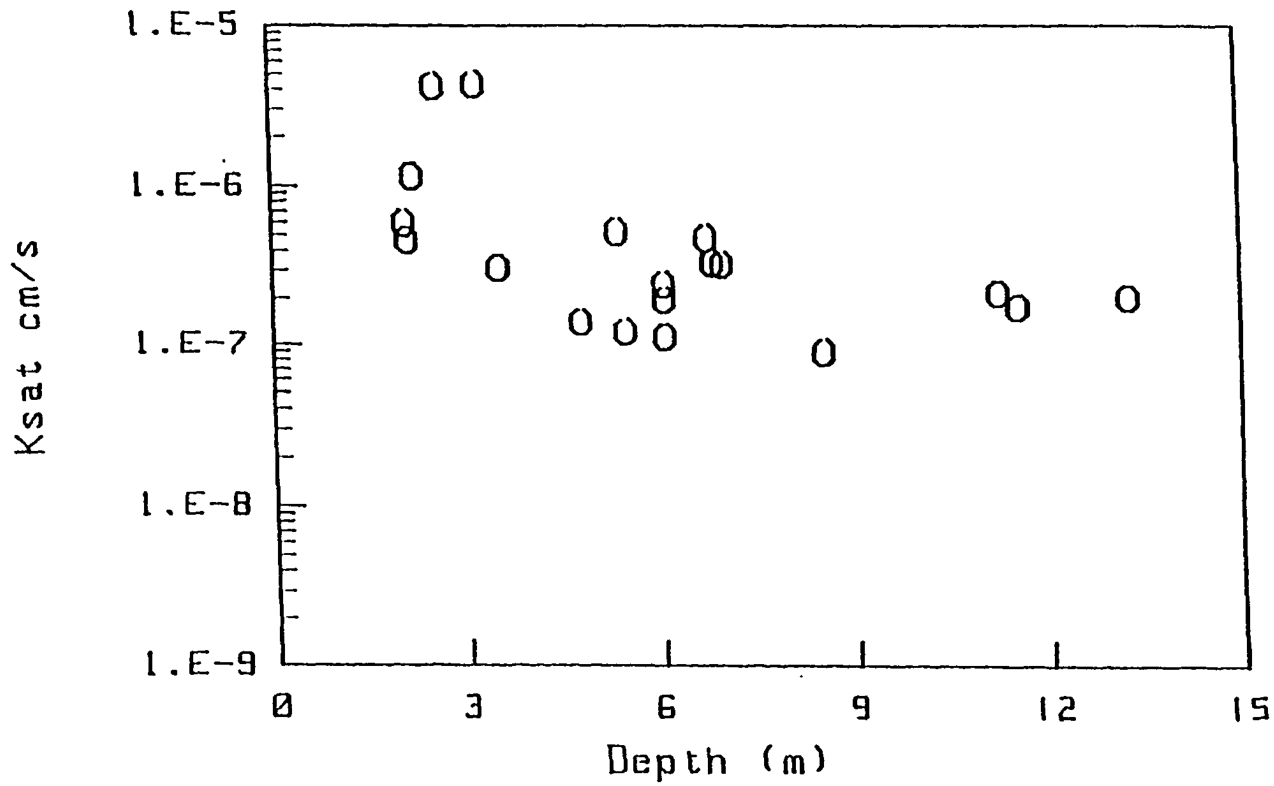

Figure 2. Saturated hydraulic conductivity with depths

Table 4. Average saturated hydraulic conductivity, K_{sat}, and dispersivity, α, values for soil samples within the Shelby tubes and soil samples removed from Shelby tubes

	K_{sat} (cm/s)	α (cm)
Samples within Shelby tubes	8.38×10^{-6}	13.45
Samples removed from Shelby tubes	5.50×10^{-7}	1.79

along the wall between the soil sample and the inside wall of the Shelby tubes.

A comparison between the breakthrough curves obtained from two soil samples before and after removing soil samples from Shelby tubes is shown in Fig. 4. Chloride breakthrough occured rapidly when measured on soil samples within Shelby tubes, however, when samples were removed from Shelby tubes and sealed into aluminum rings, about 1/4 or more pore volumes of the effluent was collected before chloride solution began to appear. Early chloride breakthrough for the soil samples within Shelby tubes again reconfirm the occurrence of side-wall flow.

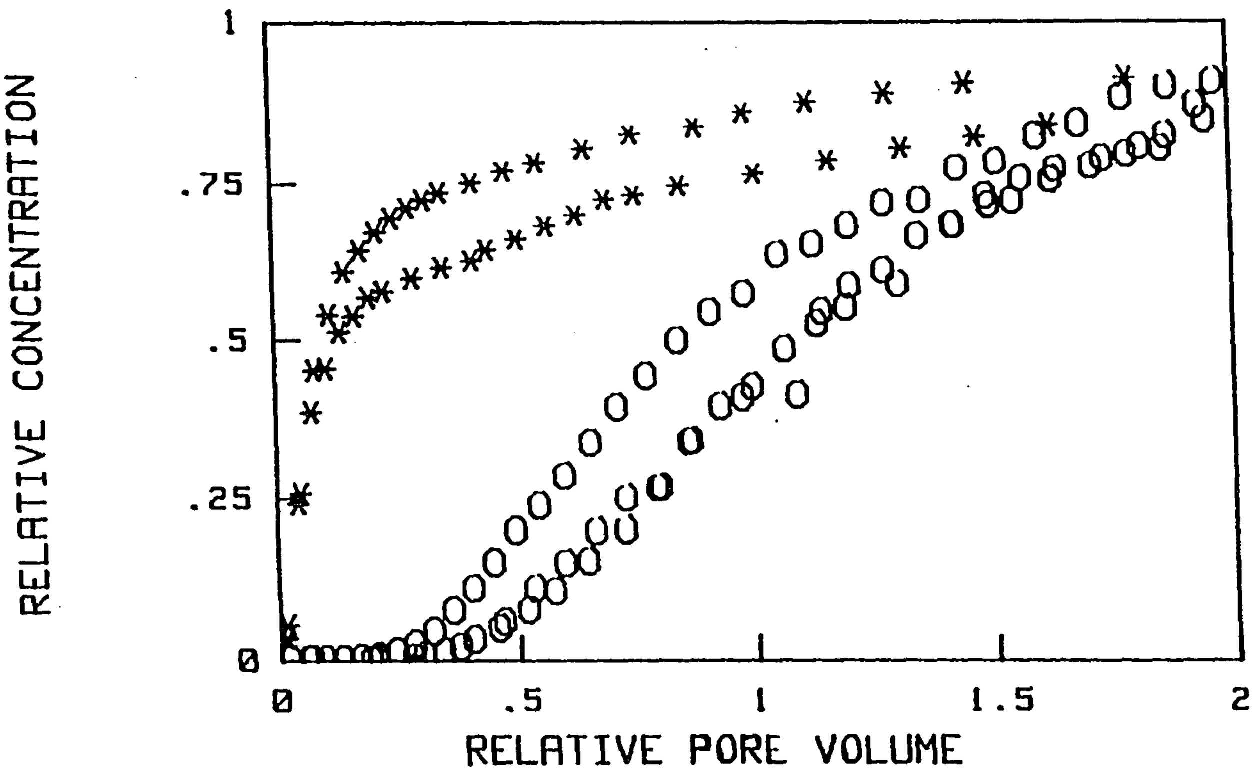

Figure 3. Chloride breakthrough curves for samples contained in Shelby tubes (*), and samples removed from Shelby tubes and sealed with paraffin wax into aluminum rings (0)

SUMMARY

The Shelby tube samples studied were uniform in particle densities and in textural composition.

Oxidized soil materials tended to have lower bulk density and higher saturated hydraulic conductivity than those of unoxidized soil materials. Bulk density increased significantly ($P \leq 0.05$) with depth.

Saturated hydraulic conductivity decreased significantly ($P \leq 0.05$) with depth down to about 9 m. Below this depth, conductivity was almost constant. Dispersivity increased slightly with depth.

Saturated hydraulic conductivity was one order of magnitude higher when measurements were conducted on the soil samples within Shelby tubes as compared with samples removed from Shelby tubes and sealed with paraffin. In addition, early chloride breakthrough and significantly higher dispersivity for the samples in Shelby tubes confirmed the occurrence of side-wall flow.

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PAPER II. TILLAGE AND TRAFFIC EFFECTS ON SOIL WATER RETENTION AND SOIL WATER, CHEMICAL, AND AIR TRANSPORT

ABSTRACT

Tillage and wheel traffic compaction can affect the physical and hydraulic properties of agricultural soils. This study was conducted to evaluate tillage and wheel traffic effects on soil physical and hydraulic properties and processes. Undisturbed soil samples were obtained from the surface A horizon of field plots which were established in fall of 1984 on a Tama silty clay loam (fine-silty, mixed, mesic Typic Argiudoll). Corn (*Zea mays* L.) and soybean [*Glycine max* (L.) Merr.] were grown in rotation on the site beginning in 1985. These samples were collected from no-till and chisel plow tillage systems and from wheel traffic and no-wheel traffic interrow positions. Bulk density, soil water retention characteristics, unsaturated and saturated hydraulic conductivities, chloride breakthrough and air permeability were measured for this evaluation. Bulk densities for no-till soil samples were higher than bulk densities for chisel plow samples. This difference in bulk density, however, was not significant. Traffic increased bulk density significantly for both tillages. Soil water retention did not differ significantly between no-till and chisel plow tillage systems at any matric potential. Traffic, however, did affect soil water retention significantly with the exception of -2, -3, and -5 kPa. No-wheel traffic samples tended to retain more water at or near saturation. Unsaturated hydraulic conductivity for chisel plow tillage systems tended to be higher than the no-till counterpart. Traffic reduced unsaturated hydraulic conductivity in both tillages. These differences in unsaturated hydraulic conductivity due to tillage

and traffic were not significant. Saturated hydraulic conductivity also did not differ significantly due to tillage but decreased significantly due to traffic. Shape and position of chloride breakthrough curves indicated that macropore flow was present in the samples. Analysis of variance for the hydrodynamic dispersion coefficient, D, and dispersivity, α, revealed nonsignificant differences between the two tillages and the traffic. Air permeability was lower for the no-till samples than for the chisel plow treatment. This difference was not significant except for matric potentials <-30 kPa. Traffic decreased air permeability significantly in both tillages.

INTRODUCTION

Excessive tillage of soil tends to facilitate erosion, therefore, interest has developed over the years in developing tillage practices that give greater protection to soil against soil and water losses. While it is well recognized that conservation tillage systems reduce both wind and water erosion (Lindstrom et al., 1979; Campbell et al., 1979; Skidmore et al., 1979; Onstad and Otterby, 1979; Voorhees et al., 1979; Onstad et al., 1982; Baker, 1987) the impact of conservation tillage on the physical and hydraulic properties of soil has been highly inconsistent (Bauder et al., 1981; Hill and Cruse, 1985; Onstad and Voorhees, 1987; Culley et al., 1987; Horton et al., 1989; Dick et al., 1989; Wagger and Denton, 1989; Wu et al., 1992).

The physical condition of a soil can be defined to a large extent by measuring the bulk density which is also a measure of porosity, soil strength and infiltration rate. The results of continuous conventional and conservation tillage treatments on bulk density in the literature are not consistent and at times are contradictory (Hill and Cruse, 1985). Some researchers (Pidgeon and Soane, 1977; Gantzer and Blake, 1978; Soane et al., 1982; Culley et al. 1987; Hill, 1990; Bicki and Guo, 1991; Meek et al., 1992) have found significant differences in bulk density between soils under conventional and conservation tillage treatment. Soane et al. (1982) have suggested that under continuous zero-tillage systems, the cycle of compaction and loosening found in arable soils subject to annual tillage no longer occurs. Mechanical loosening is not imposed other than which may be caused by the planting operation itself or any subsequent harrowing. Other researchers (Shear and Moschle, 1969; Blevins et al., 1977; Tollner et al., 1984; Hill and Cruse, 1985; Potter et al., 1985), however, have not found any significant differences in bulk density between soils under different tillage treatments.

The ability of soils to retain and transmit water is influenced by the hydraulic properties of the soil. These properties are determined by the geometry of the pore space (Klute, 1982). Tillage and compaction can alter pore geometry and consequently affect water retention and transport properties. Volumetric water content has been found to be consistently greater in soils maintained under conservation tillage systems than under conventional tillage systems (Gantzer and Blake, 1978; Negi et al., 1981; Lindstrom et al., 1984; Tollner et al., 1984). Hamblin and Tennant (1981) evaluated the influence of tillage on soil water behavior by imposing three intensities of tillage disturbance for three successive years. Their results indicated that differences in total porosity, pore-size distribution, pore geometry and water retention resulted from the various tillage treatments. No-tilled soils retained a larger volume of water than conventionally tilled soils at all matric potentials except at or near water saturation. Similar results were obtained by Allmaras et al. (1977) and Scott and Wood (1989). They found that water contents at certain values of soil water potential were lower in tilled soils than in comparable non-tilled soils.

The effects of tillage on saturated hydraulic conductivity, K_{sat}, have also been highly inconsistent. This inconsistency may be due in part to temporal variation as mentioned by Cassel (1983). Culley et al. (1987), Bicki and Guo (1991) found that K_{sat} under no-tillage exceeded those under conventional tillage despite the soil's higher bulk density, lower total porosity and greater soil strength. They suggested that macropores may be the mechanism responsible for the greater permeability. Other researchers, however, found that K_{sat} of no-tillage was either lower (Heard et al., 1988; Pikul et al., 1990) or did not differ from those under conventional tillage (Obi and Nnabude, 1988).

Literature describing the effects of tillage on unsaturated hydraulic conductivity is very limited. Negi et al. (1981), Hamblin and Tennant (1981) found that at the same volumetric water content, the unsaturated hydraulic conductivity values of tilled soils were higher than for non-tilled soils.

Use of conservation tillage typically results in increased infiltration rate of water and soil water contents and decreased water evaporation and surface runoff (Beven and Germann, 1982; Wagenet, 1987). Differences in infiltration and hydraulic conductivity in soils managed under no-till have been attributed to movement of water through large, surface-connected, continuous pores in the soil (Ehlers, 1975; Hall et al., 1987; Edwards et al., 1988). These large connected pores can conduct large amounts of water under both saturated and unsaturated conditions (Moore et al., 1986; Watson and Luxmoore, 1986; Logsdon et al., 1990). Because macropores typically occupy only a small fraction of the total soil volume, the water and dissolved (or suspended) chemicals may bypass the vast majority of soil water held in the biologically active surface horizons, increasing the possibility of groundwater contamination (Quisenberry and Phillips, 1976; Beven and Germann, 1982; Watson and Luxmoore, 1986; Dick et al., 1989). Environmental concerns have been, therefore, expressed regarding the potential of conservation tillage, and especially of no-tillage, to increase groundwater contamination by solute transport in macropore flow (Wagenet, 1987). Singh and Kanwar (1991), in solute leaching experiments conducted on saturated undisturbed soil columns, indicated a significantly greater degree of preferential flow in no-tillage columns than in conventional-tillage columns. Preferential flow indicated by rapid breakthrough was attributed to the greater number of macropores in the no-tillage columns than in the conventional-tillage columns. Similar results were obtained earlier by Kissel et al. (1973); Anderson and Bouma, (1977); and Wierenga and van Genuchten, (1989).

Air permeability has been used in attempts to characterize soil pore geometry (Ball, 1981, a,b; Hamblin and Tennant, 1981; Groenevelt et al., 1984; Groenevelt and Lemoine, 1987; Ball and O'Sulivan, 1987; Blackwell et al., 1990). Bear (1972) revealed that pore-geometric factors strongly influence soil air flow. These geometric factors include total porosity, pore size distribution, pore continuity, tortuosity, and pore shape. Evaluation of air permeability and penetrability may provide a measure of the structural degradation of soil due to intensive cultivation (Ball, 1981b; Groenevelt et al., 1984).

Air permeability measurement has been also used as a workability test for arable land (Perdok and Hendrikse, 1982). Combined with information from the moisture retention function and penetrability characteristics, a fair assessment of the structural quality, the state of compaction and root penetrability, as well as possible aeration problems, can be made (Gronenevelt and Lemoine, 1987). Roseberg and McCoy (1992) suggested that air permeability measurement and data analysis techniques afford the opportunity for more quantitative description of changes in soil macroporosity and macropore continuity due to management. They also showed that tillage had significant effects on air permeability under wheel traffic, however, tillage had no significant effects on air permeability in the absence of wheel traffic.

Soil compaction induced by wheel traffic has also been identified as a factor which affects both physical and hydraulic properties of the soil (Klute, 1982; Onstad and Voorhees, 1987; Horton et al., 1989). Wagger and Denton (1989) reported that bulk density was significantly higher in the trafficked vs. untrafficked position for Goldsboro fine sandy loam. The degree of soil compaction resulting from traffic depends on force applied and soil properties, especially soil water content (Meek et al., 1992). Hill and Meza-Montalvo (1990) observed no significant changes in soil water retention, total porosity, or pore-size distribution of the no-tilled soils that may have been attributed to wheel traffic. In conventionally tilled soils, however, they did notice changes in the physical properties that could be attributed to wheel traffic.

Ankeny et al. (1990) showed that wheel traffic greatly reduced saturated hydraulic conductivity in both no-till and chisel plow tillages. The chisel plow tillage, however, was more prone to wheel traffic compaction than no-till. Wagger and Denton (1989) also showed that soil porosity and saturated hydraulic conductivity were significantly lower in the trafficked position as compared to the untrafficked position.

Soil compaction dramatically influences solute transfer. Kluitenberg et al. (1988) compared chloride breakthrough curves for undisturbed and compacted soil samples. They found that compaction reduces the number of macropores. Hill et al. (1985) found that conventionally tilled soil had a larger proportion of macropores (>15-μm radii) and would therefore be more prone to compaction than soils under conservation tillage systems.

Early studies of gas permeability by Buehrer (1932), Kirkham (1946), Evans and Kirkham (1949), recognized the importance of air permeability as an indicator of soil structure. High permeability often indicates good structure. More recently, considerable interest has developed in air permeability as a promising tool to measure differences in pore geometry (Corey, 1986). In an attempt to quantitatively describe differences in macroporosity and macropore geometry, Roseberg and McCoy (1992) found that in wheel-traffic interrows macropore air permeability was significantly less under conventional tillage than no-tillage. They also found that wheel traffic significantly decreased air permeability for conventional tillage but not for no-tillage treatments.

In the aforementioned studies there have been inconsistencies in reported results. These inconsistencies are often caused by variance in climate, spatial and temporal variance of the soil, and spatial variance of tillage or traffic itself (Cassel, 1983). To date, few studies have included water, chemical and air movement in the same study. In addition, most of these studies have been conducted to evaluate the two extremes of the tillage spectrum, no-till and conventional tillage systems. Few studies have compared water, chemical and air movement of one of these tillage systems to more conventional conservation tillage of chisel plowing.

The objective of this study was to evaluate the effects of chisel plow and no-till tillage systems on soil water retention, water and solute movement and air permeability under trafficked and non-trafficked soil conditions.

Reliable complete information of the effects of tillage on agricultural soils would be of great benefit to agronomists and farmers in making management decisions.

MATERIALS AND METHODS

Undisturbed soil samples were obtained from the surface A horizon of field plots which were established in the fall of 1984 on a Tama soil (fine-silty, mixed, mesic typic Argiudoll) 12 km west of Marshalltown, IA. Corn (*Zea mays* L.) and soybeans [*Glycine max* (L.) Merr.] were grown in rotation on the site beginning in 1985. Soybean was grown in 1991 on the areas where soil samples were taken. Three tillage systems (no-till, ridge, and chisel plow) with controlled wheel traffic had been established on the site. Soil samples, however, were taken only from the no-till (NT) and chisel plow (CP) tillage systems. The NT plots received no primary tillage and were cultivated once a year for weed control. CP plots were chiseled in the fall, disked shortly before planting, and cultivated also for weed control. Plots were arranged in a five-row configuration in 76 cm rows and all wheel traffic was confined to the same interrows throughout the years. Within each tillage system, twelve soil samples were obtained from both wheel- and non-wheel tracked interrows. Samples were obtained from three different reps two to three weeks after cultivation.

Samples were collected by pressing galvanized metal cylinders 0.05 cm thick, 14.7 cm diameter, and 26.95 cm long into the soil about 22 cm. The cylinders were removed from the soil, placed in plastic bags, and stored at 4°C until analysis. The soil samples were removed from the metal cylinders, then trimmed to a diameter of 6.0 cm. Six centimeters of soil were also trimmed from the top and the bottom of each sample. The depth at which the soil has been evaluated in this study was from 6.0 to 15.0 cm.

Samples were sealed in polyvinyl chloride (PVC) rings (7.6 cm i.d., 8.5 cm height) with Flex-270, a rubberized asphalt product (Deery Oil, Mack, CO.). Flex-270 is commercially marketed as a low-melting-point pavement crack filler. Asphalt, instead of paraffin wax, was used as a sealer to prevent any possible failure in the seal during shrinkage of the soil samples when dried (Kluitenberg et al., 1991).

The samples were saturated from the bottom and then placed in a desorbing cell (e.g., Tempe cell). Saturated samples were subjected to a stepwise decrease in matric potentials of -1, -2, -3, -5, -10, -20, -30, and -40 kPa. Cumulative outflow volume as a function of time and equilibrium outflow volumes were measured to estimate unsaturated hydraulic conductivity from transient outflow measurements (Kool and Parker, 1987) and to determine the equilibrium water retention characteristics, respectively. Soil water retention at matric potentials of -100, -500, and -1500 kPa was determined by using a pressure-plate apparatus.

After every pressure-equilibrium step (for pressure potentials range from -1 to -40 kPa), the sample was removed from the desorbing cells, weighed to determine water content, and then air flow rate through the sample was measured using a gasometer (Evans, 1965). Air permeability was calculated by using the following equation adapted by Corey (1986) and Evans and Kirkham (1949)

$$K_a = \frac{\eta Q z}{A \Delta P} \qquad [1]$$

where K_a is air permeability (L^2), η is air viscosity ($ML^{-1}T^{-1}$), Q is the measured air flow rate (L^3T^{-1}), z is the sample height (L), A is the sample cross-sectional area (L^2), and ΔP is the pressure difference across the sample ($ML^{-1}T^{-2}$).

To measure saturated hydraulic conductivity, K_{sat} and chloride breakthrough samples were resaturated with a 0.01 N $CaSO_4$ solution for a 48-hour period. K_{sat} was determined by using a constant head method (Klute and Dirksen, 1986). Immediately after K_{sat} measurement, a chloride breakthrough experiment was conducted using a 0.05 N $CaCl_2$ solution to displace the $CaSO_4$ solution. In the displacement experiment, effluent exiting the lower boundary of the sample was collected in fractions and the chloride concentration was determined by using constant potential coulometry (Haake Buchler Digital Chloridometer).

An equation describing movement of a solute under steady-state flow conditions is (Nielson and Biggar, 1962)

$$\frac{\partial C}{\partial t} = D \frac{\partial^2 C}{\partial x^2} - v \frac{\partial C}{\partial x} \qquad [2]$$

where C is solute concentration (ML^{-3}), x is soil depth (L), t is time (T), D is the hydrodynamic dispersion coefficient (L^2T^{-1}), and v is the average pore-water velocity (LT^{-1}). Equation [2] assumes that the displacing and the displaced miscible fluids are of the same density and viscosity and that the solute does not interact with the soil (van Genuchten and Parker, 1984).

Dispersivity coefficient, α, being a characteristic property of the porous medium is estimated using the following equation

$$\alpha = \frac{D}{v} \tag{3}$$

The boundary and initial conditions used for the breakthrough experiments were the following

$$\begin{aligned} &C(x,0) = C_i \\ &C(0,t) = C_o \; ; \qquad 0 < t \leq t_o \\ &\frac{\partial C}{\partial x}(\infty,t) = 0 \end{aligned} \tag{4}$$

the solution of equation [2] is (Lapidus and Amundson, 1952)

$$C(x,t) = C_i + (C_o - C_i)\, A(x,t); \qquad 0 < t \leq t_o \tag{5}$$

where

$$A(x,t) = \frac{1}{2}\, \mathrm{erfc}\left[\frac{x - vt}{2(Dt)^{1/2}}\right] + \frac{1}{2}\exp(vx/D)\, \mathrm{erfc}\left[\frac{x + vt}{2(Dt)^{1/2}}\right] \tag{6}$$

Recommendations of using the analytical solution for a semi-infinite system to effluent data collected from a finite soil column was given by van Genuchten and Parker (1984).

Equation [5] was fitted to the breakthrough curve data by using a non-linear least squares inversion method (Parker and van Genuchten, 1984) to determine D in equation [2].

Bulk density, ρ_b, was determined on selected fragments of 45 to 60 cm^3 by using a clod method described by Blake and Hartge (1986). Particle density was determined with a pycnometer, according to Blake (1965). Particle size distribution was determined by the pipette method (Walter et al., 1978). Textural analysis indicated that the soil at the experimental site was silty clay loam with 29.6% clay, 68.0% silt and 2.4% sand.

Statistical analysis of the data was conducted using analysis of variance procedures (SAS Institute, Inc., 1985). Analysis was treated as a split plot design with tillage as main plots and traffic pattern as subplots. Mean comparisons were made using least significant differences (LSD) (Steel and Torrie, 1960). Unless a different probability level has been indicated, the 0.05 level was used to evaluate statistical significance of treatment effects and interactions in all analysis of variance procedures.

RESULTS AND DISCUSSION

Bulk Density

Tillage and traffic affected bulk density. NT soil samples exhibited greater bulk density than CP soil samples. This difference, however, was not significant ($P \leq 0.05$). Wheel traffic resulted in bulk density as high as 1.44 Mgm^{-3} and 1.42 Mgm^{-3} for NT and CP respectively. For no-wheel traffic, the bulk density was 1.32 Mgm^{-3} and 1.28 Mgm^{-3} for these tillage systems, respectively (Table 1). This increase in bulk density due to traffic was significant. The increase in bulk density due to traffic in the NT soil was small compared to the increase of bulk density in the CP soil. Soane et al. (1982) have suggested that a NT soil becomes precompacted because mechanical loosening is no longer imposed in zero-tillage systems and thereafter has sufficient soil strength to carry traffic without further change in bulk density.

Soil Water Retention

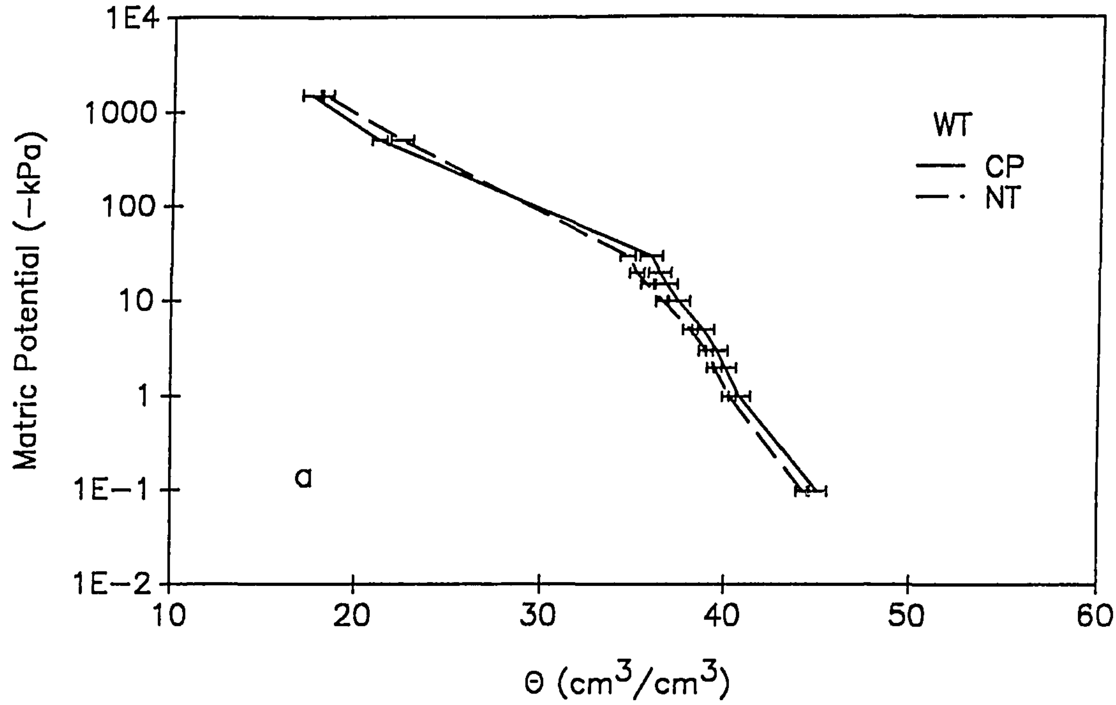
Means for soil water retention are presented in Figs. 1a and b and Figs. 2a and b. Tillage effects on soil water retention with and without wheel traffic are shown in Figs. 1a and b, respectively. There were no obvious tillage differences on soil water retention under wheel traffic (Fig. 1a). Similar to our results, Voorhees (1979) reported that wheel traffic can significantly alter the physical structure of soil and thus may diminish tillage effects. CP and NT

Table 1. Mean soil bulk densities as affected by tillage and wheel traffic.

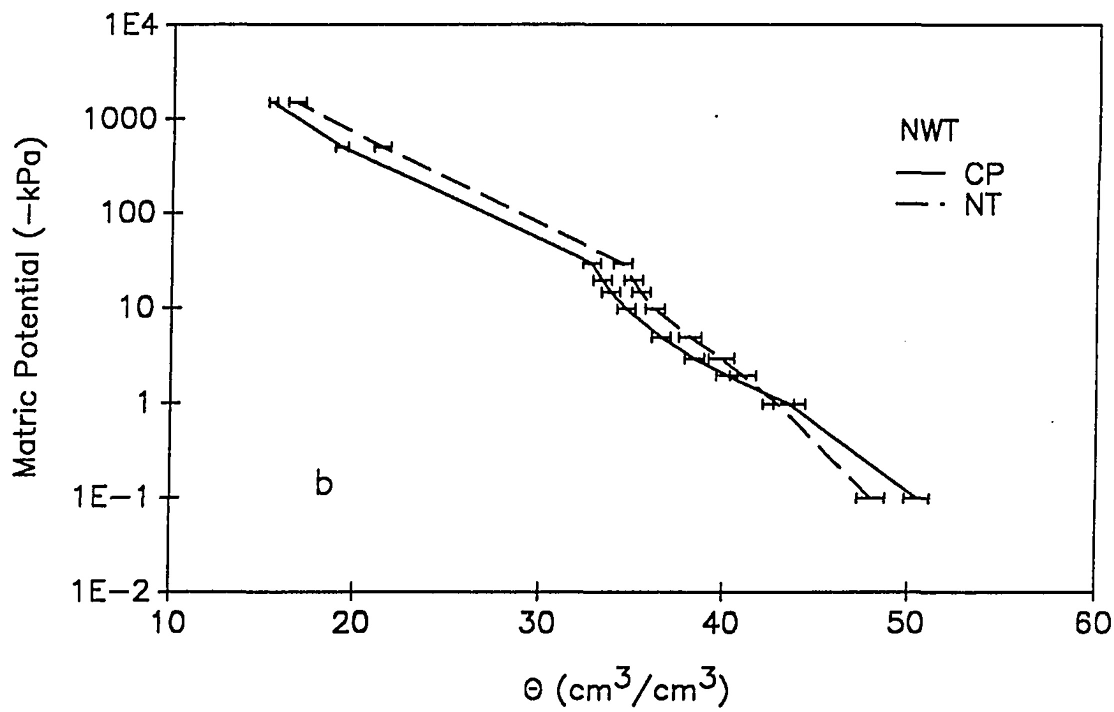
Traffic	No-till	Chisel plow
	$Mg\ m^{-3}$	
Non-Wheel	1.34	1.28
Wheel	1.44	1.42

LSD(0.05) between values within a row = 0.045
LSD(0.05) between values within a column = 0.075

Fig. 1. Mean soil water retention curves and standard error for CP and NT from wheel traffic (a) and no-wheel traffic (b).

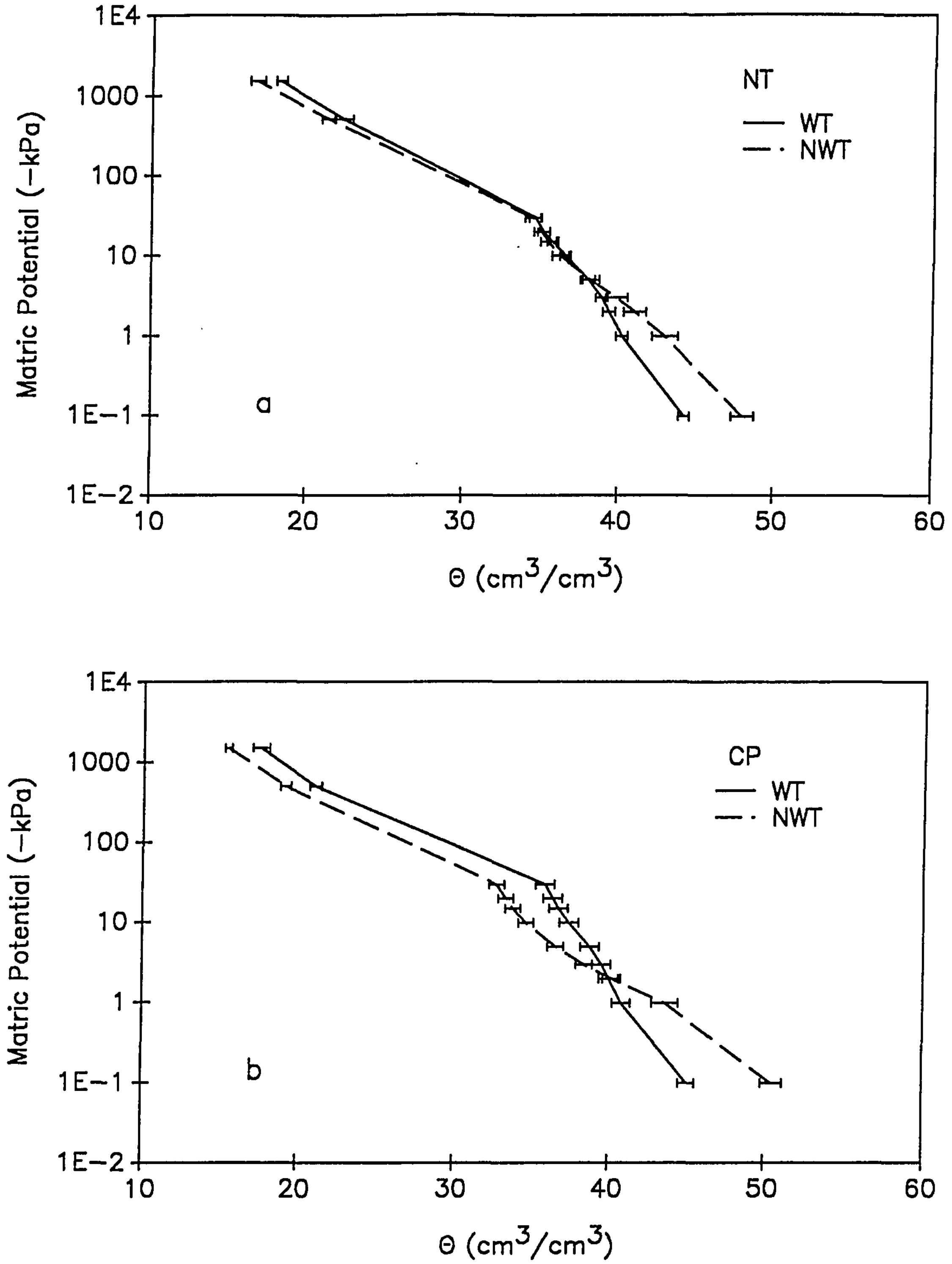


1E4
1000
100
10
1
1E−1
1E−2
Matric Potential (−kPa)
10
20
30
40
50
60
Θ (cm3/cm3)
a
WT
CP
NT



1E4
1000
100
10
1
1E−1
1E−2
Matric Potential (−kPa)
10
20
30
40
50
60
Θ (cm3/cm3)
b
NWT
CP
NT

Fig. 2. Mean soil water retention curves and standard error from wheel traffic and no-wheel traffic for NT (a) and CP (b).



1E4
1000
100
10
1
1E-1
1E-2
Matric Potential (−kPa)
10
20
30
40
50
60
Θ (cm3/cm3)
a
NT
WT
NWT
b
CP
WT
NWT

tillage treatments, however, were slightly different in soil water retention under no-wheel traffic. CP soil tended to retain more water than NT soil at 0 kPa. However, NT soil retained more water at matric potentials <-1 kPa (Fig. 1b). These observations are reflected in the non-significant tillage by traffic interaction at all matric potentials measured (Table 2).

Wheel traffic effects on soil water retention under NT and CP tillage treatments are shown in Figs. 2a and b, respectively. No-wheel traffic retained more water than the wheel traffic treatment in NT tillage systems at matric potentials of 0 and -10 kPa. Wheel traffic samples, however, retained more water at very low matric potentials <-500 kPa (Fig. 2a). For the CP tillage system, no-wheel traffic soil samples retained considerably more water than wheel traffic soil samples at 0 and -1 kPa. Wheel traffic CP soil samples, however, retained more water at matric potentials <-3 kPa (Fig. 2b). These observations are reflected in the significant effects of the traffic on soil water retention at every matric potential except -2, -3, and -5 kPa (Table 2).

A summary of significance levels for analysis of variance for soil water retention is shown in Table 2. Tillage did not affect soil water retention significantly at levels 0.01 or 0.05. Traffic, however, did affect soil water retention at the 0.01 level for 0, -1, -500, and -1500 kPa and at the 0.05 level for -10, -15, -20, and -30 kPa matric potentials. Tillage by traffic interaction was not significant at any

Table 2. Summary of significance levels for the analysis of variance of soil water retention.

		Matric Potential (-kPa)										
Source	df	0	1	2	3	5	10	15	20	30	500	1500
Rep	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Till	1	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
RepXTill	2	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS	NS
Traffic	1	**	**	NS	NS	NS	*	*	*	*	**	**
TillXTraffic	1	NS	NS	NS	NS	NS	*	*	NS	NS	NS	NS

* Significant at 0.05 level.
** Significant at 0.01 level.
NS Non-significant at the 0.05 level.

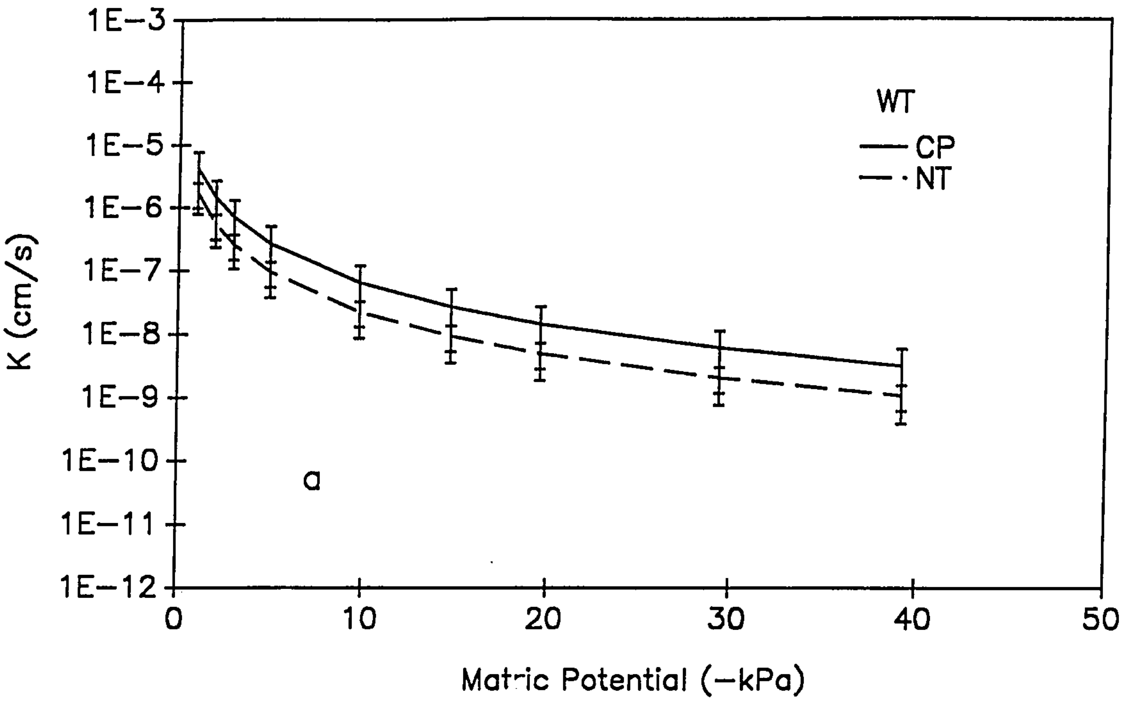
matric potential except -10 and -15 kPa.

Unsaturated Hydraulic Conductivity

For trafficked soil, CP soil had higher unsaturated hydraulic conductivity values than NT soil at all matric potentials (Fig. 3a). In non-trafficked soil, CP soil also had higher unsaturated hydraulic conductivity than NT soil but to a smaller degree (Fig. 3b). Under both tillage systems, wheel traffic caused a considerable decrease in unsaturated hydraulic conductivity (Figs. 4a and b). Allmaras et al. (1977) measured unsaturated hydraulic conductivity under NT and CP tillage systems. They found that unsaturated hydraulic conductivity values were increased at least four-fold by chiseling 0.43 m deep as compared with NT soil. Ankeny et al. (1990) revealed that traffic reduced the number of water-conducting pores and also destroyed a smaller percentage of the smaller water-conducting pores and a larger percentage of the large pores.

Analysis of variance for unsaturated hydraulic conductivity indicated that neither tillage nor traffic had significant effects. Lack of any significant tillage or traffic effects on unsaturated hydraulic conductivity may be due to the highly variable nature of these measurements. Coefficients of variation (CV) ranged from 88 to 105% at 400 and 10 kPa, respectively.

Fig. 3. Mean unsaturated hydraulic conductivity as a function of matric potential and standard error for CP and NT from wheel traffic (a) and no-wheel traffic (b).


1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
K (cm/s)
0
10
20
30
40
50
Matric Potential (-kPa)
WT
CP
NT
a

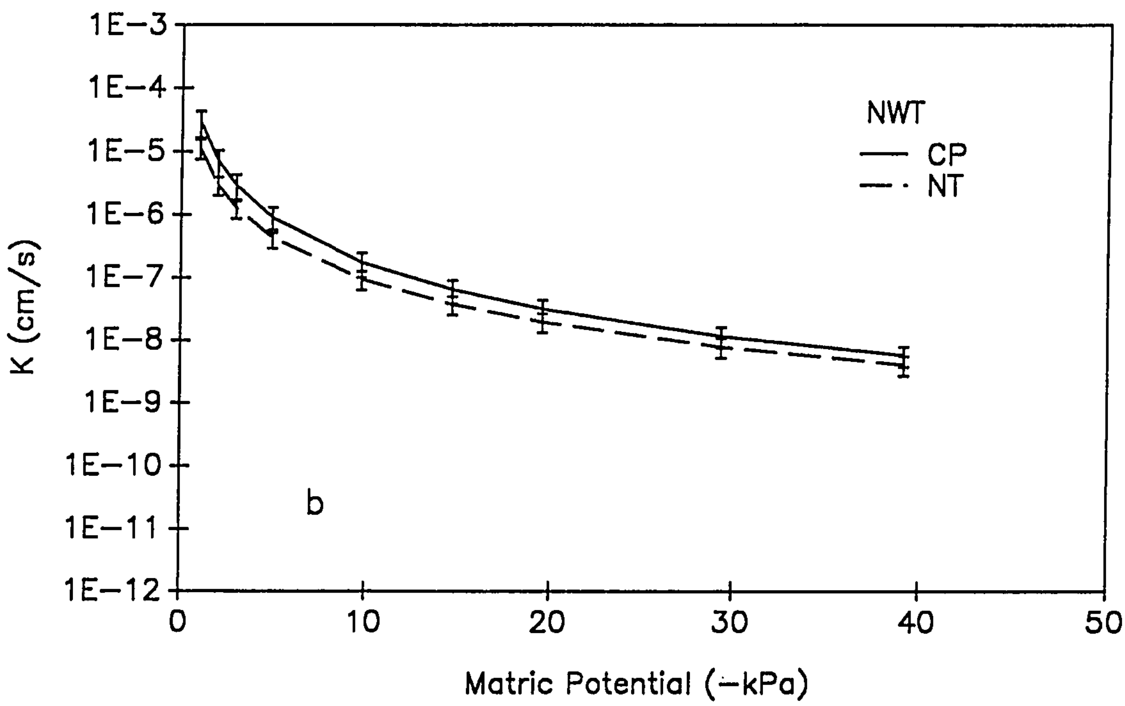
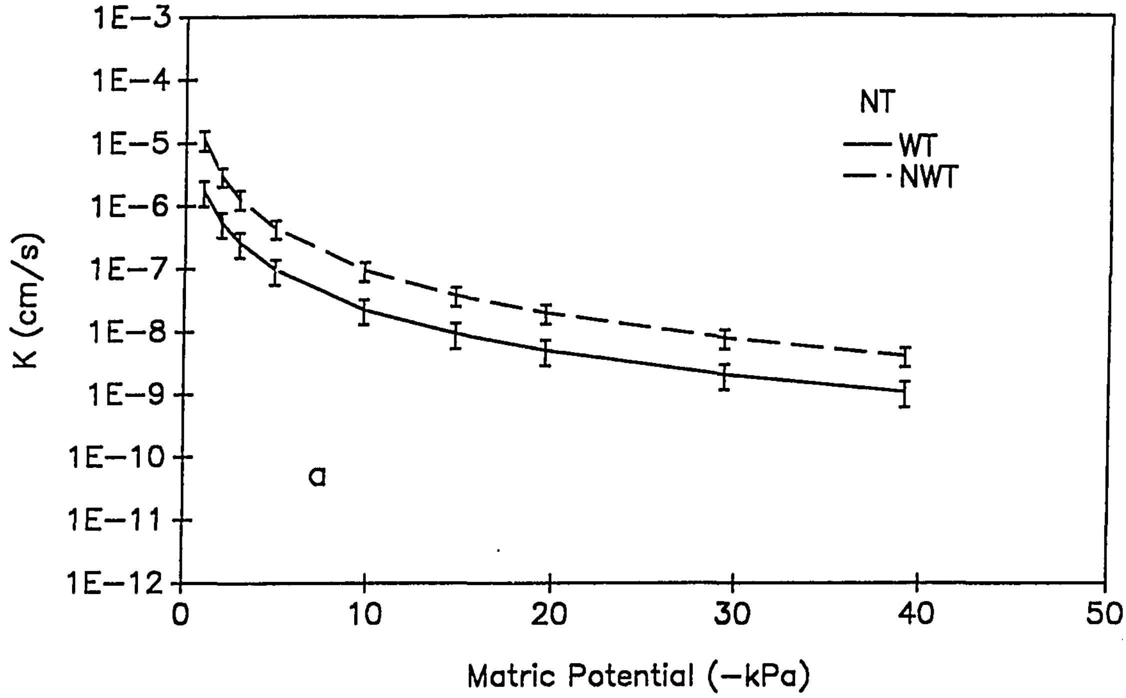
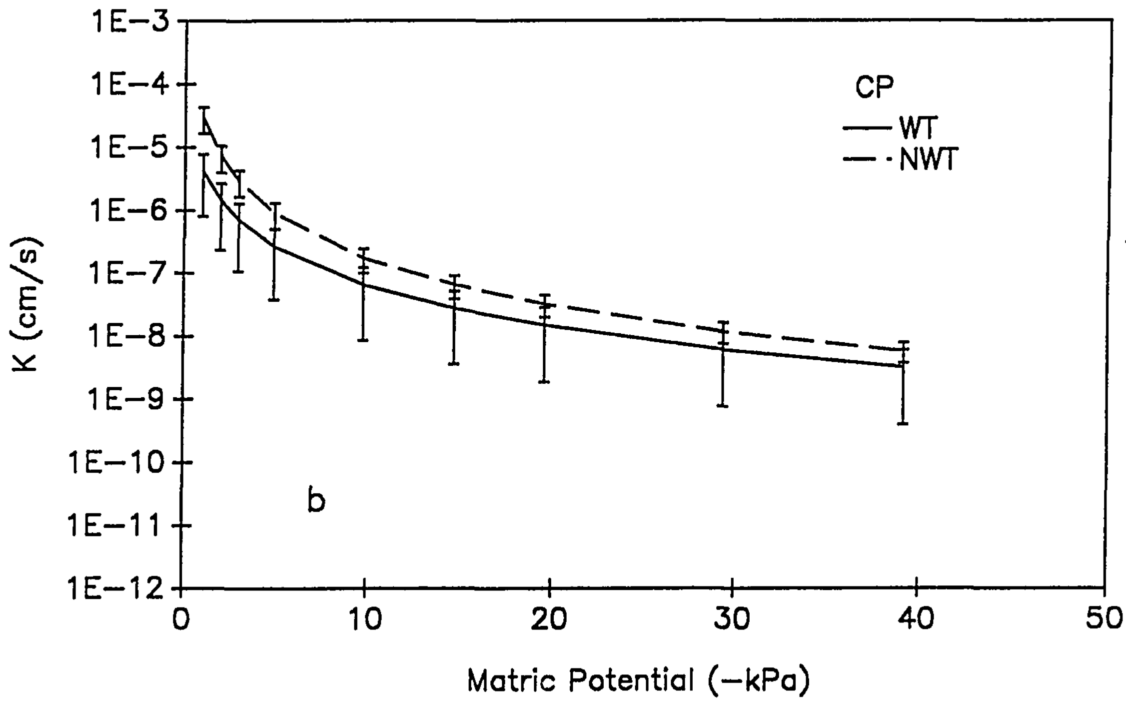

1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
K (cm/s)
0
10
20
30
40
50
Matric Potential (-kPa)
NWT
CP
NT
b

Fig. 4. Mean unsaturated hydraulic conductivity as a function of matric potential and standard error from wheel traffic and no-wheel traffic for NT (a) and CP (b).



NT
WT
NWT
a
K (cm/s)
Matric Potential (−kPa)
1E−3
1E−4
1E−5
1E−6
1E−7
1E−8
1E−9
1E−10
1E−11
1E−12
0
10
20
30
40
50



CP
WT
NWT
b
K (cm/s)
Matric Potential (−kPa)
1E−3
1E−4
1E−5
1E−6
1E−7
1E−8
1E−9
1E−10
1E−11
1E−12
0
10
20
30
40
50

Saturated Hydraulic Conductivity

Saturated hydraulic conductivity results were similar to those of bulk density with the exception that LSD showed no significant differences among the means of saturated hydraulic conductivity (Table 3). Analysis of variance, however, revealed significant differences between traffic and non-traffic soil samples for the saturated hydraulic conductivity. Tillage had no significant effects on saturated hydraulic conductivity. Hydraulic conductivity data in Table 3 shows that while tillage did not affect the conductivity, traffic did indeed reduce the conductivity.

CV was quite high (111%). Some of this variability may be attributed to sample size as reported by Sisson and Wierenga (1981).

Chloride Movement

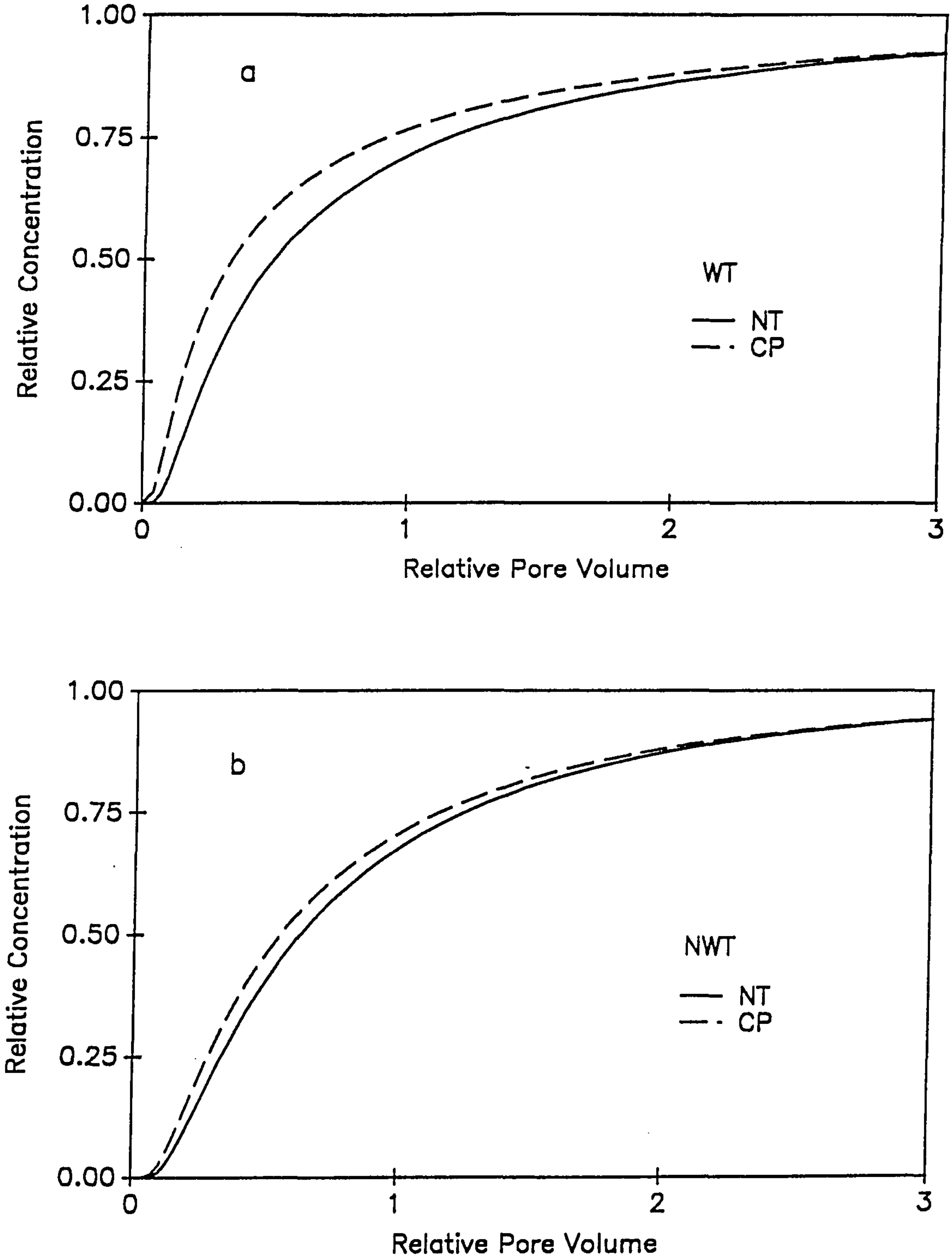
Figures 5a and b show comparisons of chloride breakthrough curves for wheel traffic and no-wheel traffic soil samples from NT and CP plots, respectively. CP soil samples from both traffic treatments showed an earlier initial breakthrough of chloride than the corresponding NT soil samples. This may have been caused by the shattering effect of chiseling. Nielson and Biggar (1961) reported that physical differences among porous materials were responsible for changes in the shape and position of breakthrough curves. Bouma and Wösten (1979) attributed a rapid chloride breakthrough from undisturbed soil columns to the presence of large continuous pores. Kanchanasut et al. (1978) pointed out that early breakthrough of tracer in an undisturbed column

Table 3. Mean saturated hydraulic conductivity as affected by tillage and wheel traffic.

Traffic	No-till	Chisel plow
	$cm\ s^{-1}$	
Non-Wheel	9.827×10^{-3}	1.023×10^{-2}
Wheel	3.615×10^{-4}	6.617×10^{-4}

LSD(0.05) between values within a row = 1.328×10^{-2}
LSD(0.05) between values within a column = 1.392×10^{-2}

Fig. 5. Mean chloride breakthrough curves for NT and CP from wheel traffic (a) and no-wheel traffic (b).


a
Relative Concentration
1.00
0.75
0.50
0.25
0.00
0
1
2
3
Relative Pore Volume
WT
NT
CP
b
Relative Concentration
1.00
0.75
0.50
0.25
0.00
0
1
2
3
Relative Pore Volume
NWT
NT
CP

was an indication of a macropore flow.

Figures 6a and b show comparisons of chloride breakthrough curves for wheel trafficked and no-wheel trafficked soil under NT and CP tillage systems, respectively. Initial chloride breakthrough for the wheel trafficked soils was unexpectedly earlier than no-wheel trafficked soil under either tillages.

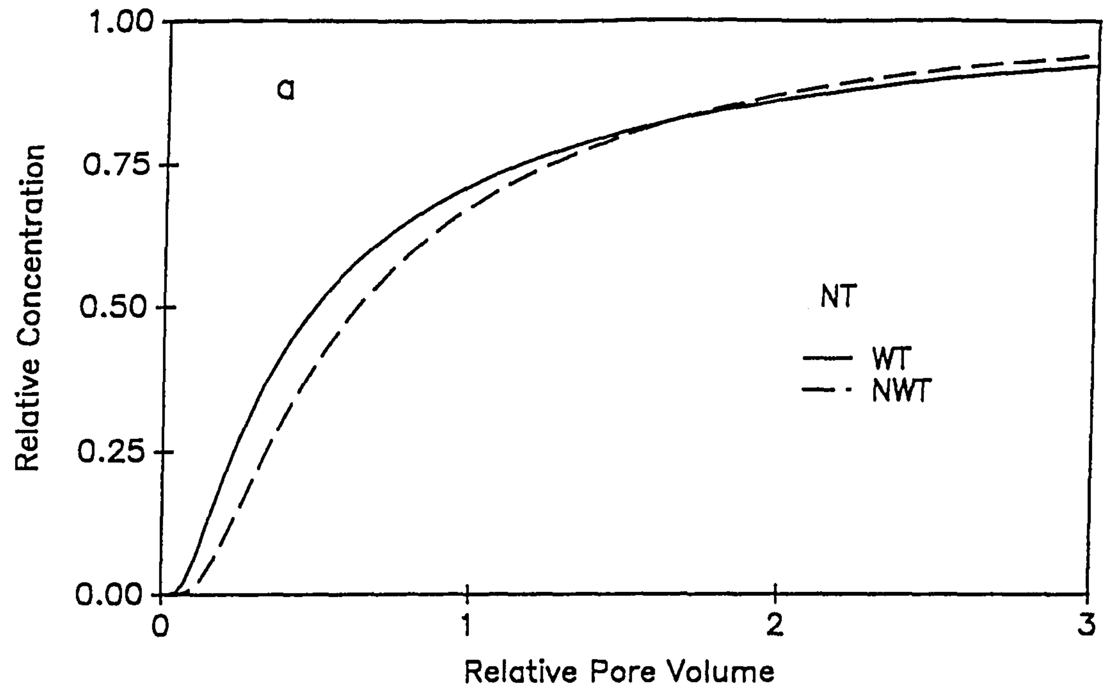
Analysis of variance for the hydrodynamic dispersion coefficient, D, and dispersivity, α, revealed non-significant effects for either tillage or traffic.

Air Permeability

Figures 7a and b show comparisons of mean air permeability values obtained at matric potentials ranging from -1 to -40 kPa, for wheel traffic and no-wheel traffic NT and CP soil samples, respectively. Tillage effects on air permeability were basically diminished under the wheel traffic treatment (Fig. 7a). Tillage, in general, had little effect on air permeability for the no-wheel traffic soil samples. CP soil samples had slightly higher air permeability values than NT soil samples at every matric potential (Fig. 7b).

Wheel traffic influence on air permeability of NT and CP soil samples are presented in Figs. 8a and b, respectively. Wheel traffic effects were substantial in both tillages (Figs. 8a and b). The reduction in air permeability by wheel traffic indicates the mitigation of pore size and the reduction of continuous air-filled pore spaces at every matric potential.

Fig. 6. Mean chloride breakthrough curves from wheel traffic and no-wheel traffic for NT (a) and CP (b).


a
Relative Concentration
1.00
0.75
0.50
0.25
0.00
0
1
2
3
Relative Pore Volume
NT
WT
NWT

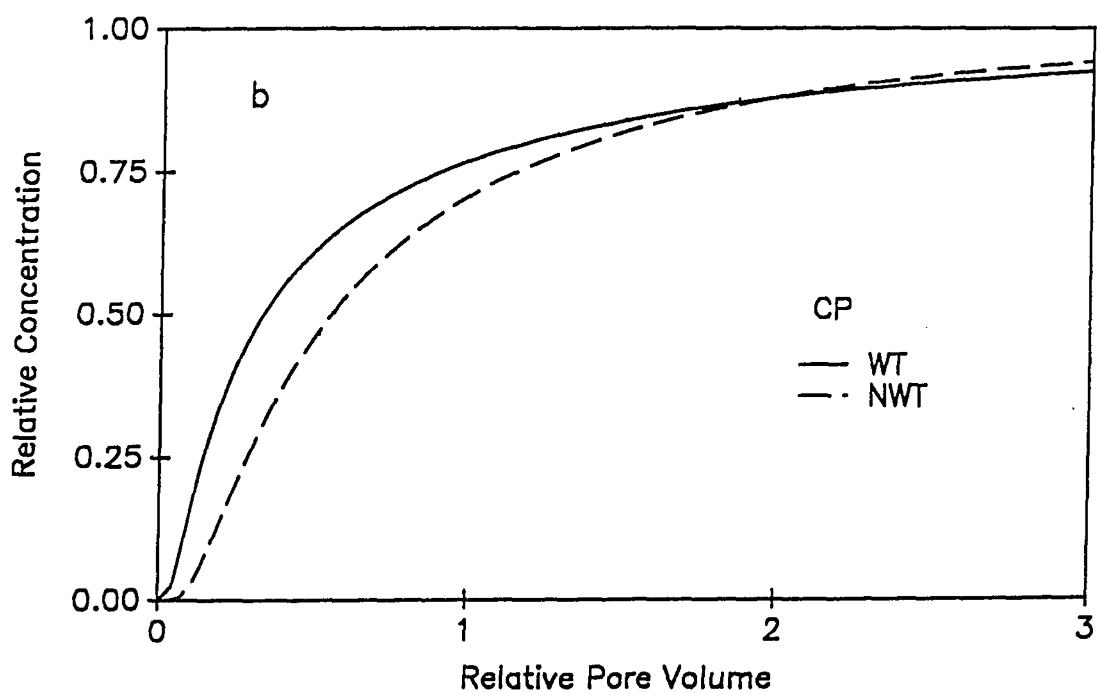
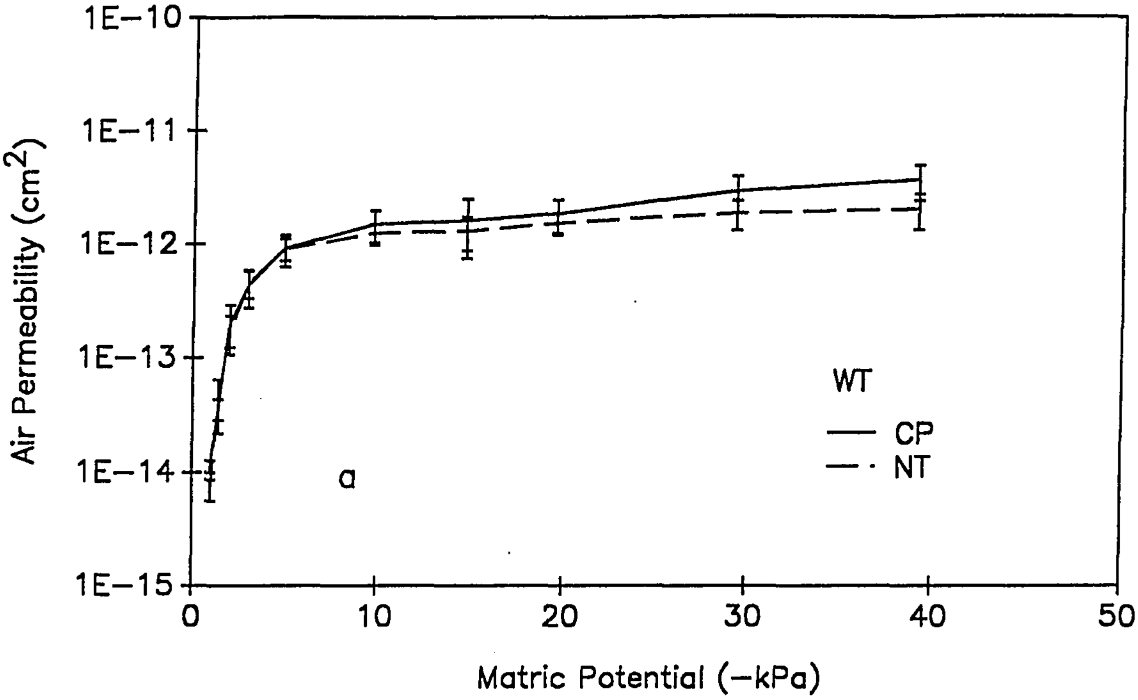

b
Relative Concentration
1.00
0.75
0.50
0.25
0.00
0
1
2
3
Relative Pore Volume
CP
WT
NWT

Fig. 7. Mean air permeability as a function of matric potential and standard error for NT and CP from wheel traffic (a) and no-wheel traffic (b).


1E−10
1E−11
1E−12
1E−13
1E−14
1E−15
0
10
20
30
40
50
Air Permeability (cm²)
Matric Potential (−kPa)
a
WT
CP
NT

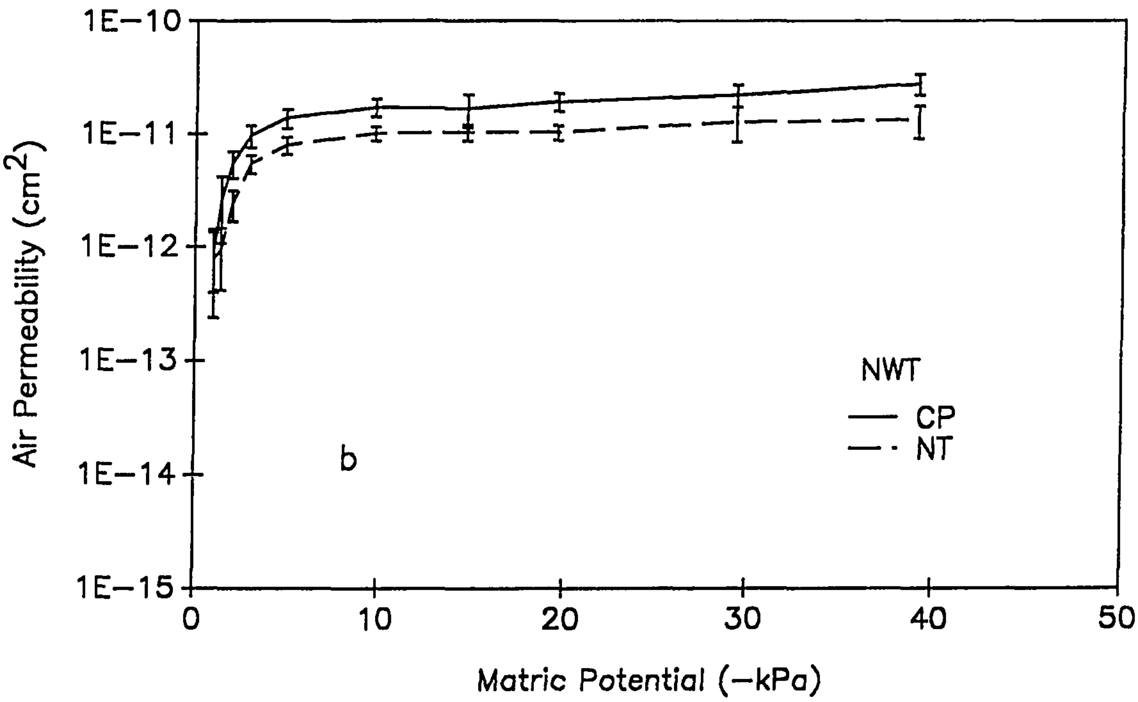
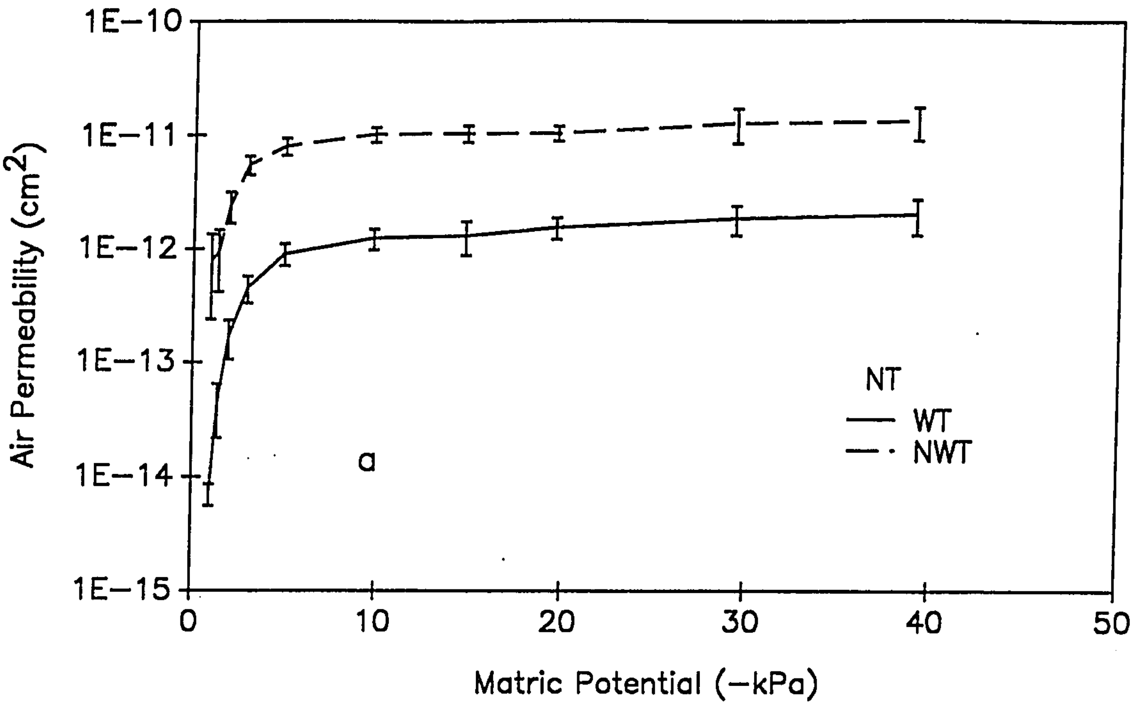
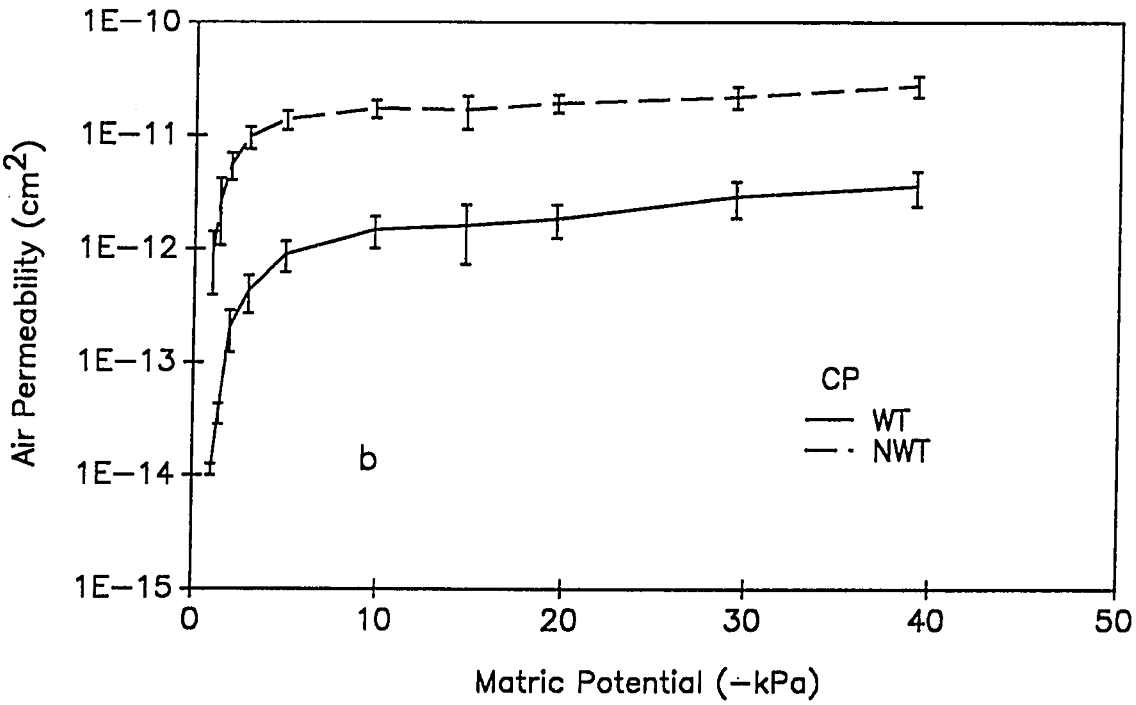

1E−10
1E−11
1E−12
1E−13
1E−14
1E−15
0
10
20
30
40
50
Air Permeability (cm²)
Matric Potential (−kPa)
b
NWT
CP
NT

Fig. 8. Mean air permeability as a function of matric potential and standard error from wheel traffic and no-wheel traffic for NT (a) and CP (b).


1E−10
1E−11
1E−12
1E−13
1E−14
1E−15
0
10
20
30
40
50
Air Permeability (cm2)
Matric Potential (−kPa)
a
NT
WT
NWT


1E−10
1E−11
1E−12
1E−13
1E−14
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0
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20
30
40
50
Air Permeability (cm2)
Matric Potential (−kPa)
b
CP
WT
NWT

Analysis of variance for air permeability revealed non-significant effects of tillage on air permeability with the exception of -30 and -40 kPa (Table 4). Traffic, however, has affected air permeability significantly at all matric potentials.

Table 4. Summary of significance levels for the analysis of variance of air permeability, K_a, at different matric potentials.

		Matric Potential (-kPa)							
Source	df	1	2	3	5	10	20	30	40
Rep	2	NS	NS	NS	NS	NS	NS	NS	NS
Till	1	NS	NS	NS	NS	NS	NS	**	*
RepXTill	2	NS	NS	NS	NS	NS	NS	NS	NS
Traffic	1	*	*	**	**	**	**	**	*
TillXTraffic	1	NS	NS	NS	NS	NS	NS	**	NS

* Significant at 0.05 level.
** Significant at 0.01 level.
NS Non-significant at the 0.05 level.

SUMMARY

Wheel traffic proved to be the dominant factor influencing the soil properties measured in this study. Bulk density increased significantly due to traffic in both NT and CP tillages. The CP tillage, however, was more susceptible to wheel traffic compaction than NT. Tillage treatment did not influence bulk density significantly.

Soil water retention was influenced significantly by traffic with the exception of -2, -3, and -5 KPa. Tillage, however, showed no significant differences in the amount of water retained. Saturated hydraulic conductivity results were similar to that of bulk density in that only the traffic effect was significant. Unsaturated hydraulic conductivity, K(h), was increased by chiseling as compared to NT. However, this increase was not significant statistically. Traffic reduced unsaturated hydraulic conductivity for both tillages. This reduction was also not significant. Chloride breakthrough experiments revealed early initial breakthrough of chloride in all samples; indicating the occurrence of preferential flow. Initial breakthrough of chloride appeared earlier in CP than in NT regardless of the traffic treatment. Statistical analysis of variance for the hydrodynamic dispersion coefficient, D, and dispersivity, α, revealed nonsignificant effects for both tillage and traffic. Air permeability was increased by chiseling as compared to NT. This increase was not significant except at matric potential <-30 kPa. Traffic, however, reduced air permeability significantly for both tillages.

It can be inferred from this study that the effects of tillage and traffic for the properties measured were consistent. The increase in bulk density occurred primarily at the expense of larger pores. The shrinkage of the larger pores caused a decrease in saturated and unsaturated hydraulic conductivities and also a reduction in air permeabilities at every matric potential. Air permeability showed the greatest change of all properties measured.

Lack of statistical significance due to tillage may be a result of weed control cultivation which was performed a few weeks before collecting the soil samples. The relatively high coefficients of variation with the soil property measurements may necessitate more intensive sampling or perhaps larger sample sizes.

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PAPER III. PREDICTING UNSATURATED HYDRAULIC CONDUCTIVITY FROM UNSATURATED AIR PERMEABILITY MEASUREMENTS

ABSTRACT

Unsaturated hydraulic conductivity is an important soil parameter that affects the transport of water and solutes in soil. Unfortunately, direct measurement of unsaturated conductivity is both difficult and time consuming. Therefore, numerous methods have been proposed to estimate unsaturated hydraulic conductivity from more easily measured soil properties. Air and water are two fluids that share occupancy in soil pores. Flow properties of these two fluids are interrelated and therefore, it is conceptually possible to estimate the conductivity of one fluid from knowledge of the other. In this study we present and evaluate a method of estimating unsaturated hydraulic conductivity from air permeability data. Twelve undisturbed soil samples of Tama silty clay loam (fine-silty, mixed, mesic typic Argiudoll) were obtained from the surface A horizon of field plots. Samples were collected from the middle of wheel traffic and no-wheel traffic interrows. Air permeabilty of each sample was measured at selected soil matric potentials. A theoretical model relating air permeability to air filled porosity was developed. The model contains a parameter that can be used to predicte unsaturated hydraulic conductivity. The model parameter was determined for each soil samples by curve fitting the model to the measured air permeability data. The model parameter for each sample was then used to predict unsaturated hydraulic conductivity for each sample. Predicted unsaturated hydraulic conductivity values from air permeability were compared to estimated values, from transient outflow method. The results of this

study indicate that unsaturated hydraulic conductivity can be estimated reasonably well from air permeability data. The prediction of unsaturated hydraulic conductivity by this model was consistently reliable over a range of bulk densities.

INTRODUCTION

Hydraulic conductivity is an important property which affects the transport of water and solutes in soil. Most processes involving water flow in the vadose zone occur under unsaturated conditions. Unfortunately, direct measurements of the unsaturated hydraulic conductivity are tedious, time consuming, and considerably uncertain (Russo et al., 1991), since they often entail changes in the state and content of soil water during the flow process (Hillel, 1980). Therefore, numerous methods have been proposed to estimate hydraulic conductivity indirectly from more easily measured soil properties, such as soil texture, organic matter, and bulk density (Clapp and Hornberger, 1978; Bloemen, 1980; Schuh and Bauder, 1986).

Much attention has been devoted to the use of pore-size distribution functions obtained from soil water retention curves for predicting hydraulic conductivity. Among the most popular methods have been Millington and Quirk (1961), Brooks and Corey (1964), Campbell (1974) and more recently van Genuchten (1978 and 1980).

Application of predictive pore-size distribution models often requires independent estimates of the water retention curve $h(\theta)$. Unfortunately, most available retention functions can not be easily incorporated into these pore-size distribution models to yield relatively simple closed-form analytical expressions for hydraulic conductivity (van Genuchten and Leij, 1992). Exceptions are the equations of Brooks and Corey (1964), Campbell (1974), and van Genuchten (1980).

Results to date suggest that predictive models work reasonably well for many coarse and medium-textured soils, but predictions for fine-textured soils and most structured soils remain somewhat unreliable (van Genuchten and Leij, 1992).

Another important soil property is air permeability. Early researchers such as Buehrer (1932), Kirkham (1946), Evans and Kirkham (1949), and Reeve (1953) used air permeability as a promising tool to measure differences in pore geometry (Corey, 1986). By measuring the air permeability of soil, one can obtain useful information regarding the geometry of its air filled pores (Groenevelt and Lemoine, 1987). Soil pore geometric factors, i.e., total porosity, tortuousity, shape and pore continuity, strongly influence soil air flow (Bear, 1972). Several efforts have attempted to evaluate the functional relationships between mass flow and pore geometric factors using air permeability (Ball, 1981; Hamblin and Tennant, 1981; Groenevelt et al., 1984; Douglas et al., 1986; Ball et al., 1988). Air permeability measurements combined with information from the moisture retention function and penetrability characteristics would give a fair assessment of the structural quality and the state of compaction, as well as possible aeration problems (Groenevelt and Lemoine, 1987). Taylor and Ashcroft (1972) and Corey (1986) showed that gas permeability measurements would be improved if they could be measured as a function of moisture content. For soils at equal gas-filled porosities, the presence of macropores has been shown to increase air permeability (Ball, 1981).

Air and water are two fluids occupying similar pore spaces in the soil. Flow properties of these two fluids are interrelated, and, therefore, it is conceptually possible to estimate the conductivity of one fluid from knowledge of the other.

The use of air transport properties for this purpose, however, is often overlooked. The available published information on the relationship between air flow and water flow is limited a few studies (Brooks and Corey, 1964; Parker et al., 1987; Mousli et al., 1992).

The use of air to study the hydraulic properties of porous media has several advantages over the use of water. Experiments with gases in the unsaturated soil can be performed quickly and easily replicated.

The objective of this study is to evaluate the relationship between air permeability and water permeability. An attempt is made to estimate unsaturated hydraulic conductivity from the more easily measured unsaturated air permeability.

THEORY

The following model was presented by Mualem (1976) to predict relative hydraulic conductivity using information from a water retention curve

$$K_{rw} = \Theta^{\frac{1}{2}} \left\{ \int_0^{\Theta} [1/h(x)]dx \Big/ \int_0^1 [1/h(x)]dx \right\}^2 \qquad [2]$$

where $K_{rw}=K_w/K_{wm}$, K_w is unsaturated hydraulic conductivity, K_{wm} is maximum conductivity (i.e. saturated hydraulic conductivity), h is the pressure head which is a function of the dimensionless water content, Θ:

$$\Theta = (\theta - \theta_r) / (\theta_s - \theta_r) \qquad [3]$$

where θ is water content, θ_r is residual water content, and θ_s is saturated water content.

Mualem's equation is actually a simple integral formula for unsaturated hydraulic conductivity which enables one to derive closed-form analytical expressions, provided suitable equations for the soil-water characteristic curves are available (van Genuchten, 1980). Equation [2] is similar to Childs and Collis-George (1950) model but uses a modified assumption concerning the hydraulic conductivity of the pore sequence in order to take into account the effect of the large pore section (Mualem, 1976).

Van Genuchten (1980) proposed the following expression for water retention relationships:

$$\Theta = \left[\frac{1}{1 + (\alpha h)^n}\right]^m \qquad [4]$$

where α, n, and m, are parameters that can be determined by curve fitting equation [4] to soil water characteristic data.

Van Genuchten (1980) combined equations [4] and [2], set m = [1-(1/n)] and evaluated the integrals to find a closed form equation for K_{rw}

$$K_{rw}(\Theta) = \Theta^{\frac{1}{2}}\left[1 - \left(1 - \Theta^{1/m}\right)^{m}\right]^{2} \qquad [5]$$

where m = [1-(1/n)] is the same m as in equation [4]. Thus, once equation [4] is curve fit to water retention observations, the n parameter can be used in equation [5] to predict relative unsaturated hydraulic conductivity.

Relative hydraulic conductivity may also be expressed in terms of the pressure head by substituting equation [4] into equation [5]

$$K_{rw}(h) = \frac{\left\{1 - \left(\alpha h\right)^{n-1}\left[1 + \left(\alpha h\right)^{n}\right]^{-m}\right\}^{2}}{\left[1 + \left(\alpha h\right)^{n}\right]^{m/2}} \qquad [6]$$

In order to estimate relative hydraulic conductivity from air permeability, K_a, measurements, one can extend Mualem's model to the gas phase similar to Parker et al. (1987) by using

$$\Phi = (\phi - \phi_{min}) / (\phi_{max} - \phi_{min}) \qquad [7]$$

where Φ is reduced air content, ϕ is air content, ϕ_{min} is the minimum air content, ϕ_{max} is the maximum air content.

Where $\phi = \theta_s - \theta$, $\phi_{min} = 0$, $\phi_{max} = \theta_s - \theta_r$

Then

$$\Phi = (\phi / \phi_{max}) = (\theta_s - \theta) / (\theta_s - \theta_r) \qquad [8]$$

Therefore,

$$\Phi = 1 - \Theta \qquad [9]$$

Substitution of equation [9] into [4] gives

$$(1 - \Phi) = \left[\frac{1}{1 + (\alpha h)^n} \right]^m \qquad [10]$$

Equation [10] can also be written in terms of the pressure head, h,

$$h(\Phi) = \frac{1}{\alpha} \left[\frac{(1 - \Phi)^{1/m}}{1 - (1 - \Phi)^{1/m}} \right]^{-1/n} \qquad [11]$$

Substitution of equation [11] into [2] gives

$$K_{ra}(\Phi) = \Phi^{1/2} \left\{ \int_0^{\Phi} [(1 - x)^{1/m} / 1 - (1 - x)^{1/m}]^{1/n} \, dx \, / \right.$$

$$\left. \int_0^1 [(1 - x)^{1/m} / 1 - (1 - x)^{1/m}]^{1/n} \, dx \right\}^2 \qquad [12]$$

Integration of equation [12] gives

$$K_{ra}(\Phi) = \Phi^{1/2} \, [1 - (1 - \Phi)^{1/m}]^{2m} \qquad [13]$$

Equation [13] can also be written in terms of reduced water content as follows

$$K_{ra}(\Theta) = \left(1 - \Theta\right)^{1/2} \left(1 - \Theta^{1/m}\right)^{2m} \qquad [14]$$

where K_{ra} is the relative air permeability (= K_a/K_{am}), K_{am} is the maximum air permeability.

The parameter m can be determined by curve fitting equation [14] to measured K_a data. Substitution of m into equation [5] provides estimated values of K_r.

Theory regarding the interrelationships among the variables Θ, Φ,

K_{rw}, K_{ra} is presented in equations [7] through [14]. The theory is developed for isotropic soil materials. The theory is applicable to soil having unimodel pore-size distribution, since the van Genuchten (1980) Eq. has been found to describe for media with a unimodal pore-size distribution (Durner, 1992).

MATERIALS AND METHODS

Twelve undisturbed soil samples were obtained from the surface A horizon of field plots which were established in the fall of 1984 on a Tama soil (fine-silty, mixed, mesic typic Argiudoll) 12 km west of Marshalltown, Iowa. Corn (*Zea mays* L.) and soybeans [*Glycine max* (L.) Merr.] were grown in rotation on the site beginning in 1985. Soybeans were grown in 1991 on the areas where the soil samples were taken. Controlled wheel traffic had been established on the site.

Samples were collected from the middle of wheel traffic and no wheel traffic interrows. Galvanized metal cylinders (0.05 cm wall thickness and, 14.7 cm diameter), were pressed about 20 cm into the soil. The cylinders were removed from the soil, placed in plastic bags, and stored at 4°C until analysis. The soil samples were removed from the metal cylinders, then trimmed to a diameter of 6.0 cm and a length of about 8.5 cm. Samples were sealed into polyvinyl chloride (PVC) rings (7.6 cm i.d., 8.5 cm height) with Flex-270, a rubberized asphalt product (Deery oil, Mack, CO.). Flex-270 is commercially marketed as a low-melting-point pavement crack filler. Asphalt was used as a sealer to prevent failure in the seal during shrinkage of soil samples when desaturated (Kluitenberg et al., 1991).

The samples were saturated from the bottom and then placed in a desorbing cell (e.g., Tempe cell). Saturated samples were subjected to a stepwise decrease in matric potentials of -1, -2, -3, -5, -10, -20, -30, and -40 kPa. Cumulative water outflow volume as a function of time and equilibrium outflow volumes were measured to estimate unsaturated hydraulic conductivity from transient outflow measurements (Kool and Parker, 1987), and to determine soil water content at every equilibrium step. Saturated hydraulic conductivity was also determined for each sample using a constant head method (Klute and Dirksen, 1986).

To measure air permeability as a function of matric potential, samples were resaturated and again placed in the desorbing cell apparatus. Samples were subjected to a stepwise decrease in matric potentials of -1, -2, -3, -5, -10, -20, -30, and -40 kPa. After every pressure equilibrium step samples were removed from the desorbing cells, weighed to determine water content, and then air flow rate through the samples was measured using a gasometer (Evans, 1965). A separate sequence of desorption was necessary for the air permeability measurements because at each pressure equilibrium step a soil sample was removed from the desorption apparatus in order to measure K_a. The interruption in water outflow by moving the samples in and out of the desorbing cells was undesirable for the measurement of unsaturated hydraulic conductivity.

Air permeability was calculated by using the following equation adapted by Corey (1986) and Evans and Kirkham (1949)

$$K_a = (\eta Qz) / (A \, \Delta P) \qquad [1]$$

where K_a is air permeability (L^2), η is air viscosity ($ML^{-1}T^{-1}$), Q is the measured air flow rate (L^3T^{-1}), z is the sample height (L), A is the sample cross-sectional area (L^2), and ΔP is the pressure difference across the sample ($ML^{-1}T^{-2}$).

Bulk density, ρ_b, was determined on selected fragments of 45 to 60 cm^3 by using a clod method described by Blake and Hartge (1986). Particle density was determined with a pycnometer, according to Blake (1965). Particle size distribution was determined by the pipette method (Walter et al., 1978).

The procedure for using air permeability measurements to estimate unsaturated hydraulic conductivity includes the following steps:

1- use desorption apparatus to control soil matric potential.

2- measure water retention curve.

3- estimate unsaturated hydraulic conductivity from transient outflow method at selected soil matric potentials.

4- measure air permeability at selected soil matric potentials.

5- estimate θ_r from water retention data by using nonlinear compute program (Leij et al., 1992).

6- estimate K_{am} from $K_a(\Theta)$ data.

7- estimate parameter m in Eq. [14] by curve fitting the equation to $K_{ra}(\Theta)$ data.

8- insert m estimated from $K_{ra}(\Theta)$ data in step 7 into Eq. [5] in order to estimate unsaturated hydraulic conductivity values.

9- compare estimated hydraulic conductivity values from Eq. [5] with measured hydraulic conductivity values (step 3).

RESULTS AND DISCUSSION

The means of bulk density for samples obtained from non-wheel traffic and wheel traffic were 1.33 Mg m^{-3} and 1.42 Mg m^{-3}, respectively. Particle density was found to be 2.6 Mg m^{-3}. Textural analysis indicated that the soil was silty clay loam with 29.6% clay, 68.0% silt and 2.4% sand.

Parameters m estimated from fitting Eq. [14] to air permeability data, and from fitting Eq. [5] to water retention data are presented in Table 1. Air permeability data and water retention data provided similar values of m.

Figures 1 and 2 show typical observed and fitted soil water characteristic curves for the soil samples used in this study. The shape of these curves reflect the pore-size distribution and is typically affected by soil structure and textural class. In general, the greater the clay content, the greater water retention at any particular soil matric potential, and the more gradual the slope of the curve. Saturated water content for these samples varied from 42.82% to 49.95% . Wheel traffic reduced significantly the amount of water retained in the soil at 0 kPa. These figures also show that these curves are not approaching an asymptote, over the range of matric potentials considered in this study (0 to -1500 kPa).

Curves of $K(\theta)$ for both air permeability and water conductivity are shown in Figs. 3 and 4 for untrafficked and trafficked soil, respectively. The $K(\theta)$ functions shown are expressed as relative permeability which in this case is defined as K_a/K_{am} for air permea-

Table 1. The values of m parameter obtained from fitting equation [5] to $h(\theta)$ data and equation [14] to $K_{ra}(\theta)$ data.

Sample	m From Eq. [5]	m From Eq. [14]
a	0.119	0.128
b	0.113	0.114
c	0.127	0.128
d	0.098	0.092
e	0.138	0.119
f	0.092	0.130
g	0.117	0.125
h	0.126	0.114
i	0.117	0.169
j	0.104	0.161
k	0.091	0.113
l	0.091	0.078

Figure 1. Water retention curves and fitted curves to Eq. [5] for untrafficked soil

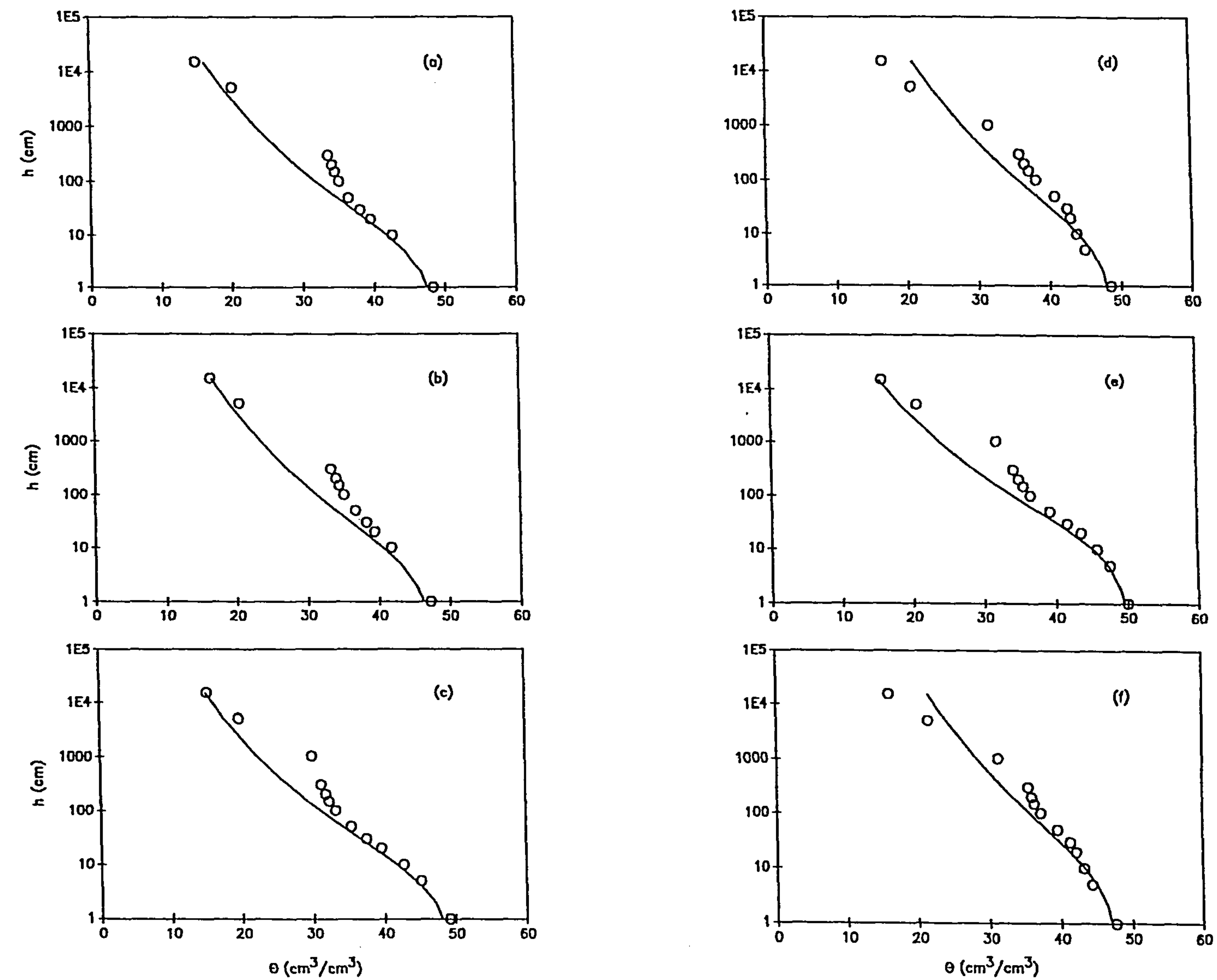
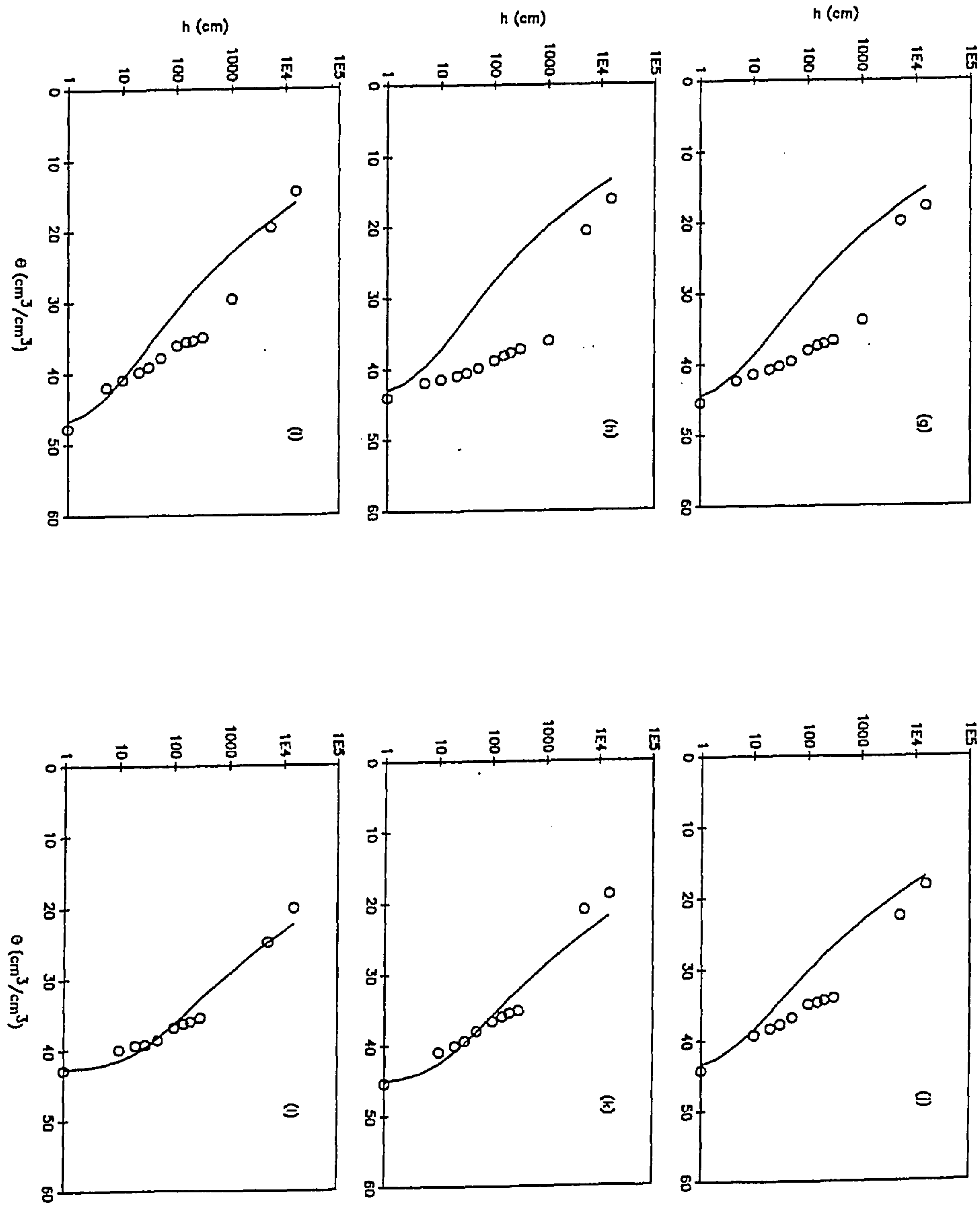

(a)
(b)
(c)
(d)
(e)
(f)
h (cm)
1E5
1E4
1000
100
10
1
0
10
20
30
40
50
60
θ (cm3/cm3)

Figure 2. Water retention curves and fitted curves to Eq. [5] for wheel trafficked soil

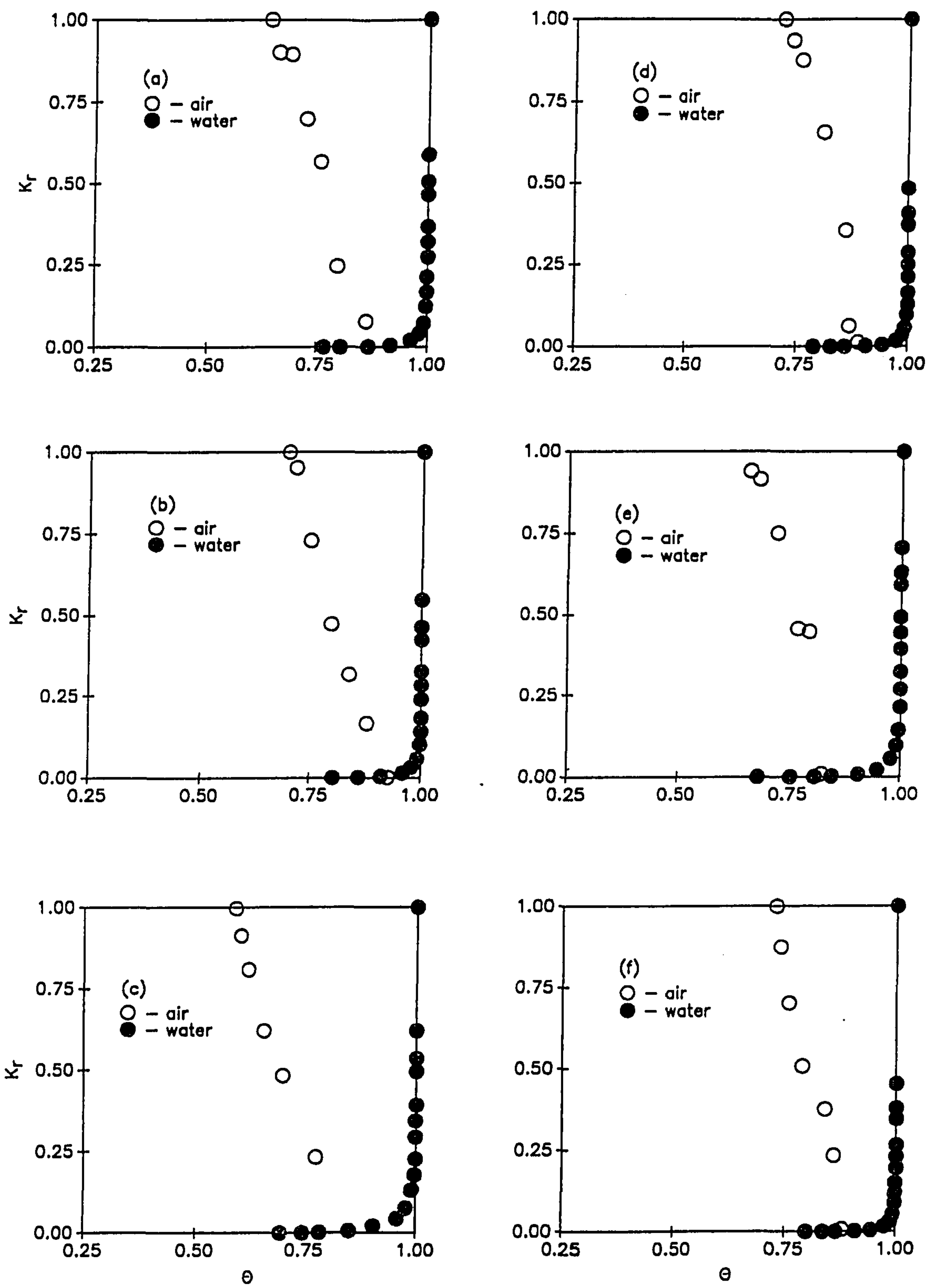


(g)
(h)
(i)
(j)
(k)
(l)
h (cm)
θ (cm³/cm³)

bility and K_w/K_{wm} for unsaturated hydraulic conductivity, in which the subscripts (am and wm) refer to the maximum value of K for the particular fluid under consideration (i.e. air, water). K_{am} for air permeability was defined in this study as the maximum value measured. This approach seems logical because K_a increased as matric potential decreased. K_a leveled off until it was somewhat constant as matric potential approached -40 kPa (Figs. 3 and 4). Brooks and Corey (1964) estimated K_{am} in a similar manner. K_{wm} is the actual saturated hydraulic conductivity. K/K_{wm} is referred to as relative water conductivity or relative water permeability.

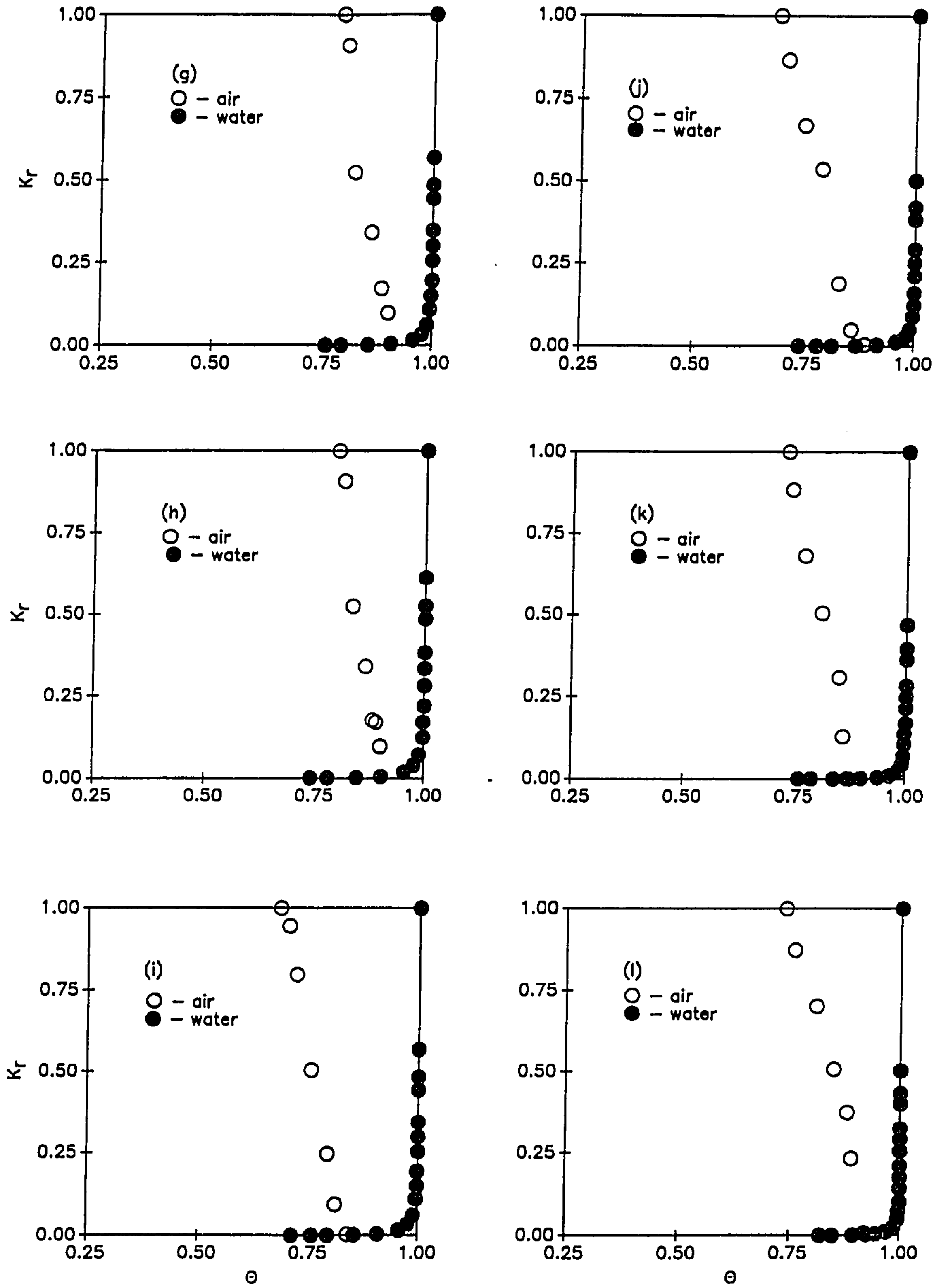
Figures 3 and 4 show that the relative water permeability drops sharply when air enters the soil system. Relative hydraulic conductivity reaches a very small value while the reduced water content, θ, is still considerably greater than zero (e.g. 57-77%). Soil air permeability does not exist until some water has drained from the sample (approximately 5% of total amount of water). Figures 3 and 4 also show that the relative air permeability of samples reach maximum values at relatively high reduced water contents. These water contents coincide with the values of reduced water content at which K_{rw} approach zero. These results demonstrate some consistency in air and water flow for these samples. When saturated samples are subjected to a slight suction (exceeding air entry), the largest pores begin to empty and consequently, water hydraulic conductivity decreases sharply. As suction is increased, more water is drained out of the soil sample, and more of the relatively large pores, which cannot

Figure 3. Relative water permeability (solid circles) and relative air permeability (opened circles) as functions of reduced water content for untrafficked soil samples.



(a)
○ – air
● – water
(b)
○ – air
● – water
(c)
○ – air
● – water
(d)
○ – air
● – water
(e)
○ – air
● – water
(f)
○ – air
● – water
K_r
1.00
0.75
0.50
0.25
0.00
0.25
0.50
0.75
1.00
θ

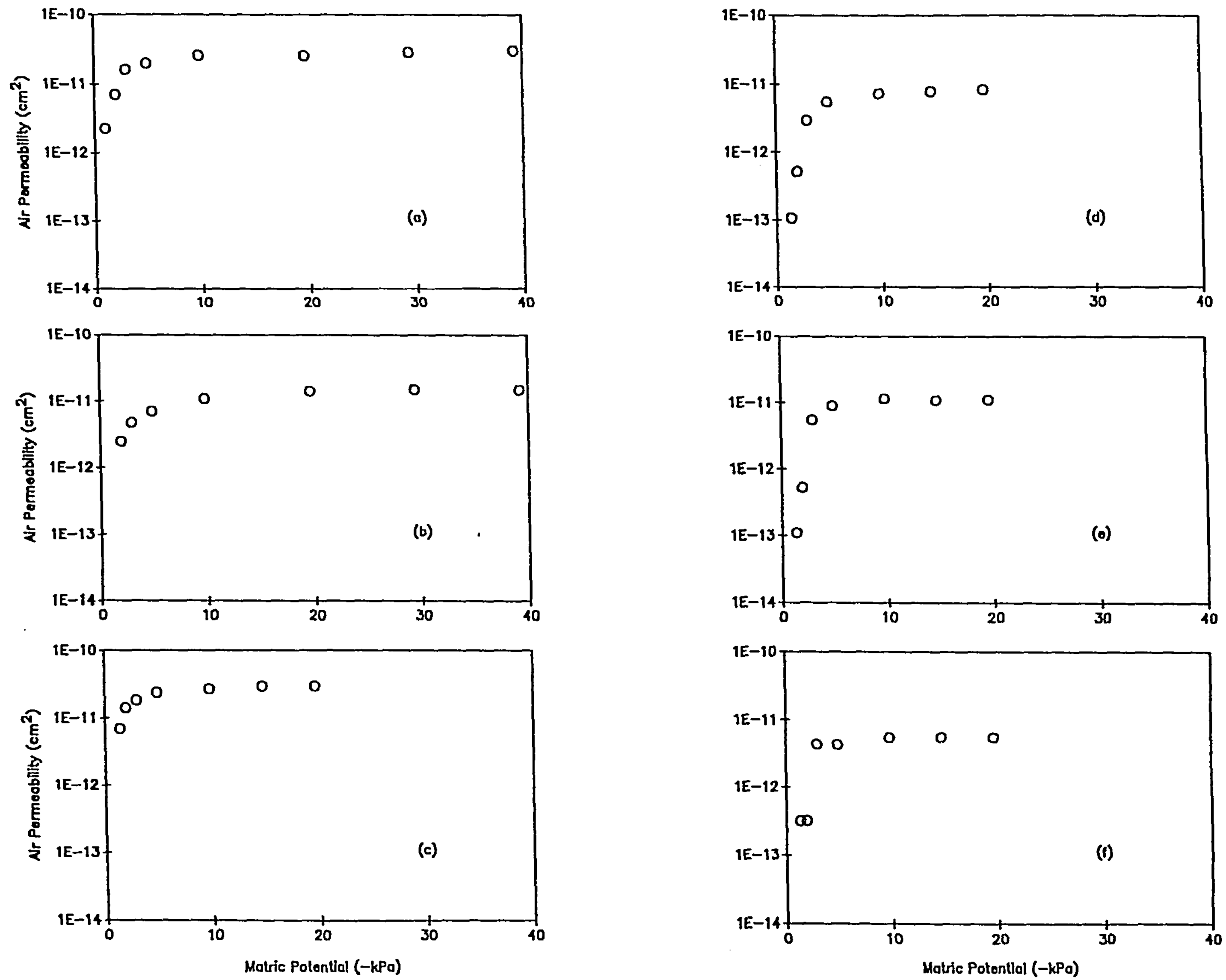
Figure 4. Relative water permeability (solid circles) and relative air permeability (opened circles) as functions of reduced water content for wheel trafficked soil samples.


(g)
○ – air
● – water
(j)
○ – air
● – water
(h)
○ – air
● – water
(k)
○ – air
● – water
(i)
○ – air
● – water
(l)
○ – air
● – water
K_r
1.00
0.75
0.50
0.25
0.00
0.25
0.50
0.75
1.00
Θ

retain water against the suction applied, are emptied, causing further decreases in hydraulic conductivity. Since the soil samples used in this study were undisturbed samples and contained secondary soil structure, the decrease in water conductivity was distinct and sharp. As the relatively large pores emptied, the air permeability increased relatively quickly. Furthermore, as the matric potential decreased, smaller and smaller pores emptied, and the air permeability increased at a progressively decreasing rate until it reached a somewhat constant value below -10 kPa (Figs. 5 and 6). However, the rate at which air permeability increased was less than the rate that unsaturated hydraulic conductivity decreased. Ball (1981) indicated that air permeability not only depends on the radius of the largest air filled pore but on the pore length and continuity as well.

Figures 7 and 8 show estimated (from transient water outflow) and predicted (from air permeability) hydraulic conductivity as a function of soil matric potential for untrafficked and trafficked soil samples, respectively. These results were consistent, in that, as matric potential decreased hydraulic conductivity decreased as well. These figures also show that predicted hydraulic conductivity curves agreed very well with the estimated ones, for the majority of the samples used in this study. Furthermore, application of the relative air permeability model proposed in this paper consistently lead to a good agreement between predicted hydraulic conductivity values and the estimated data, for both untrafficked and trafficked soil. The results

Figure 5. Air permeability as a function of matric potential for untrafficked soil samples



Air Permeability (cm²)
1E-10
1E-11
1E-12
1E-13
1E-14
(a)
(b)
(c)
(d)
(e)
(f)
0
10
20
30
40
Matric Potential (-kPa)

Figure 6. Air permeability as a function of matric potential for wheel trafficked soil samples

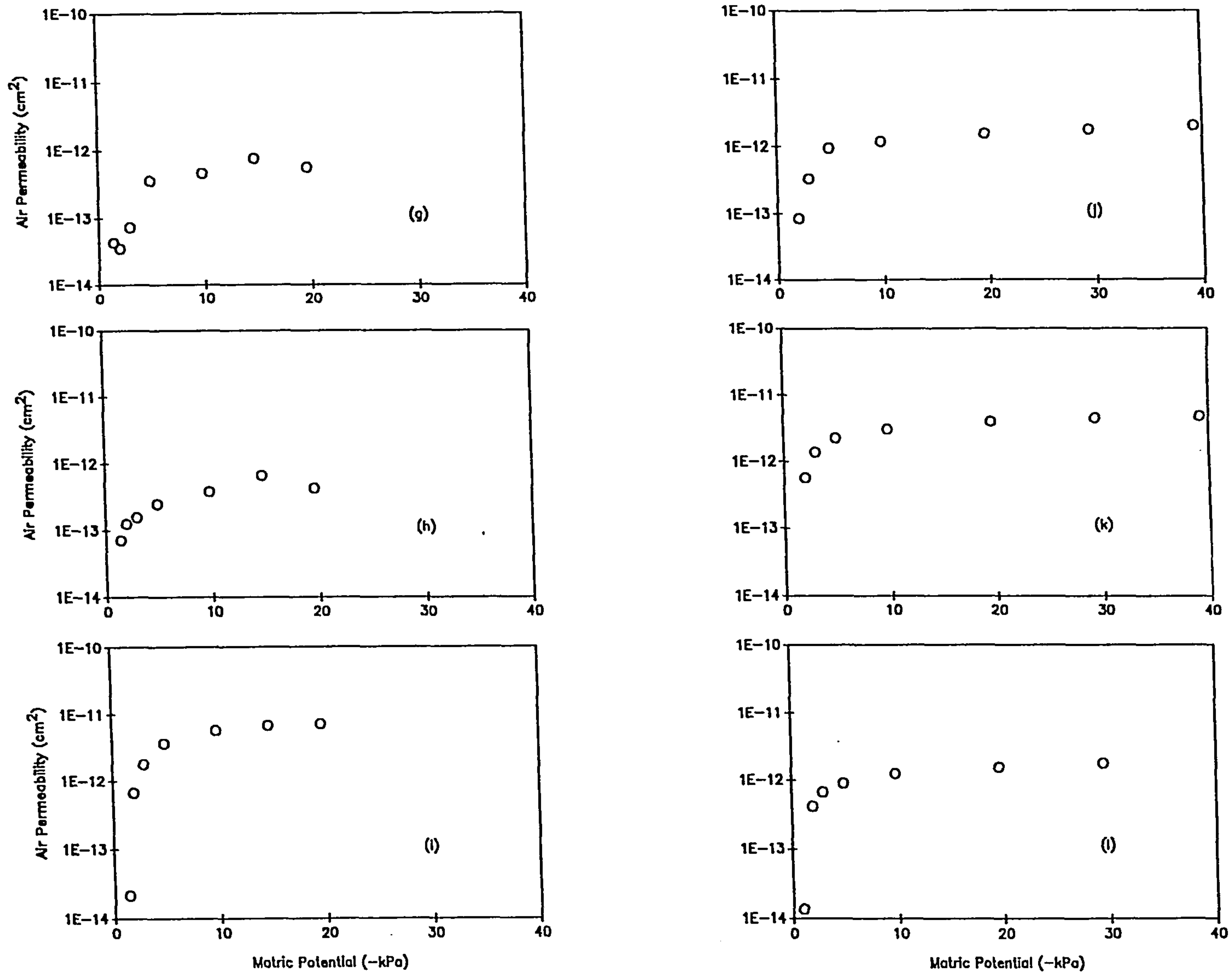

Air Permeability (cm²)
1E-10
1E-11
1E-12
1E-13
1E-14
0
10
20
30
40
(g)
(h)
(i)
(j)
(k)
(l)
Matric Potential (-kPa)

Figure 7. Estimated unsaturated hydraulic conductivity from transient water outflow method (dashed lines) and predicted unsaturated hydraulic conductivity from air permeability (soild lines) for untrafficked soil samples

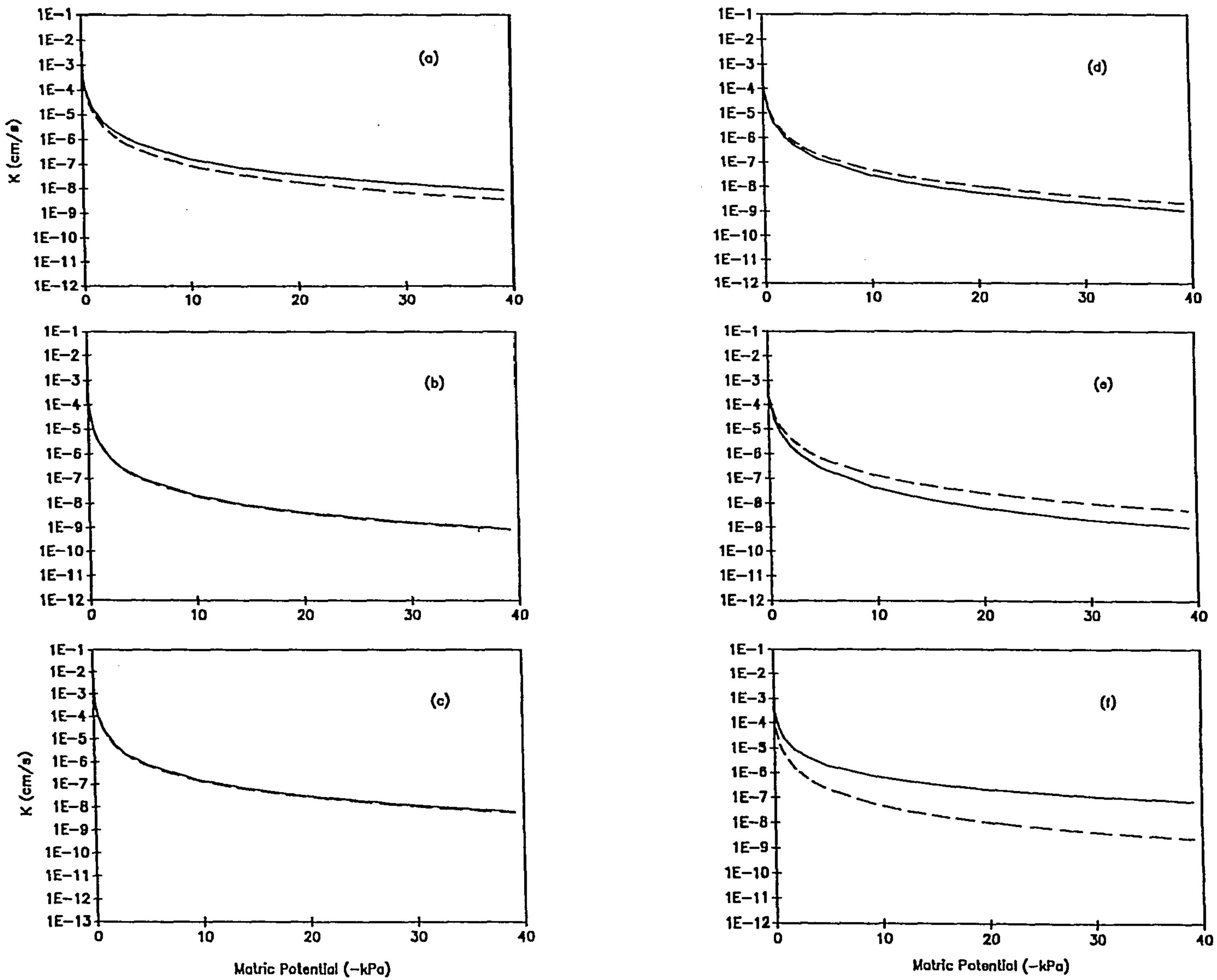
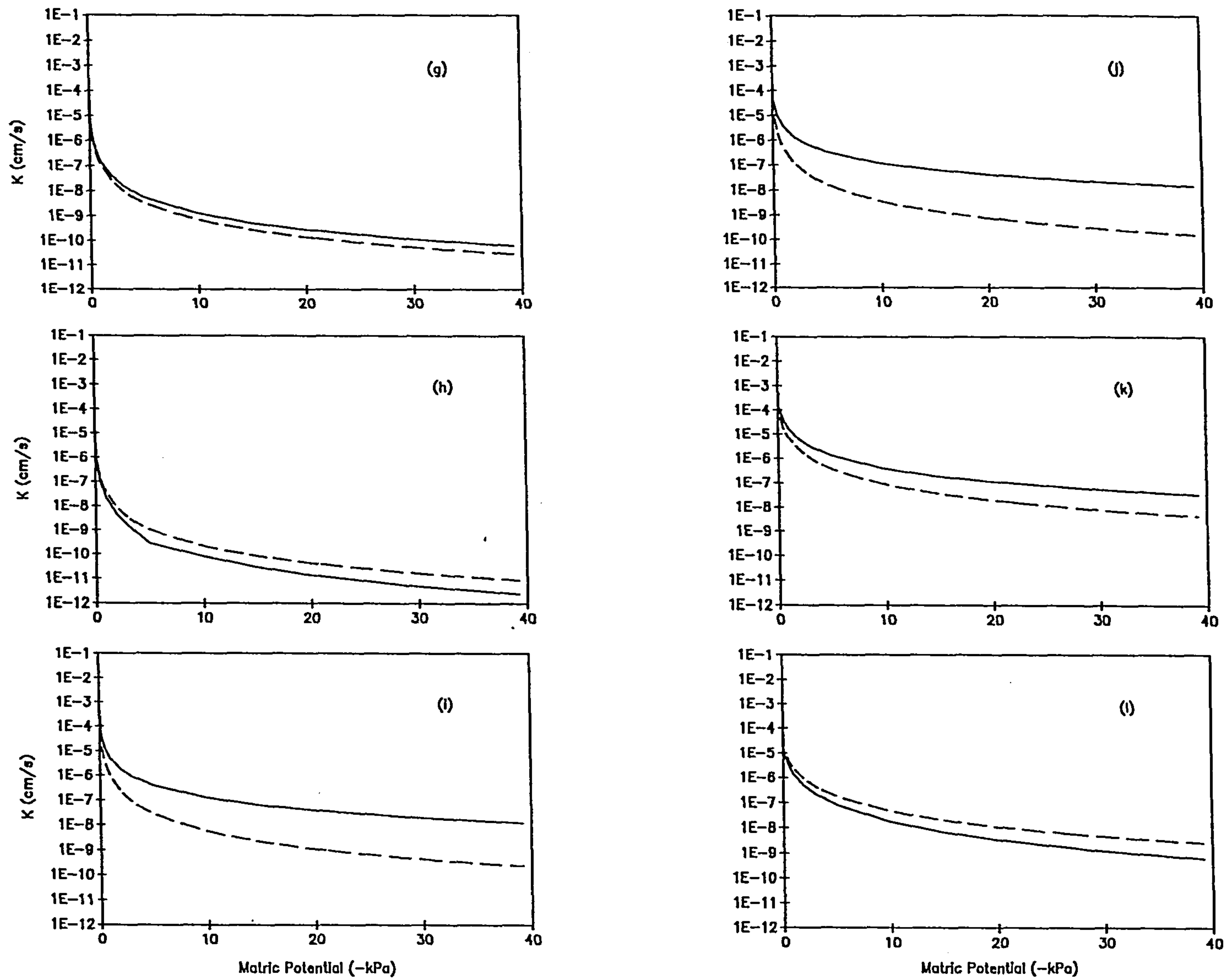

(a)
(b)
(c)
(d)
(e)
(f)
K (cm/s)
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
1E-13
0
10
20
30
40
Matric Potential (-kPa)

Figure 8. Estimated unsaturated hydraulic conductivity from transient water outflow method (dashed lines) and predicted unsaturated hydraulic conductivity from air permeability (solid lines) for wheel trafficked soil samples


(g)
(h)
(i)
(j)
(k)
(l)
K (cm/s)
1E-1
1E-2
1E-3
1E-4
1E-5
1E-6
1E-7
1E-8
1E-9
1E-10
1E-11
1E-12
0
10
20
30
40
Matric Potential (-kPa)

of this study indicate that the method of using air permeability to predict hydraulic conductivity of soil is reliable over a range of bulk densities. The approach of using air permeability to predict unsaturated hydraulic conductivity is simple, convenient and promising. Further research of this method should be undertaken for a variety of soil types.

Although the approach of using unsaturated air permeability to predict unsaturated hydraulic conductivity was accurate, one feature is in need of more understanding. The theoretical model describing air permeability as a function of air filled porosity did not always describe the observed air permeability values well (Figs. 9 and 10). Further research to understand the shortcomings of the model and to develop and test additional models is needed.

Figure 9. Measured air permeability (opened circles) and theoretical air permeability (soild circles) estimated from Eq. [14] for untrafficked soil samples

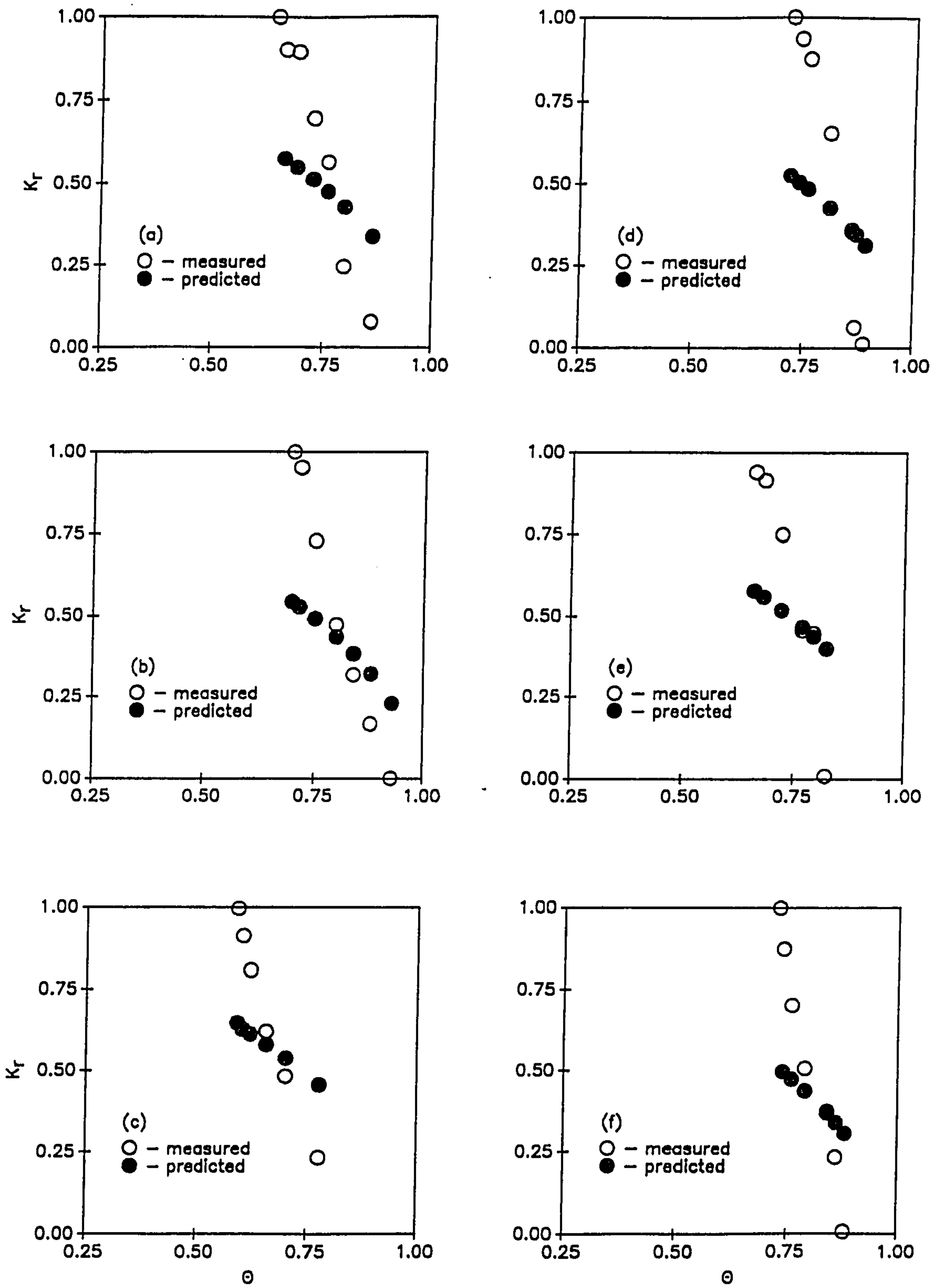
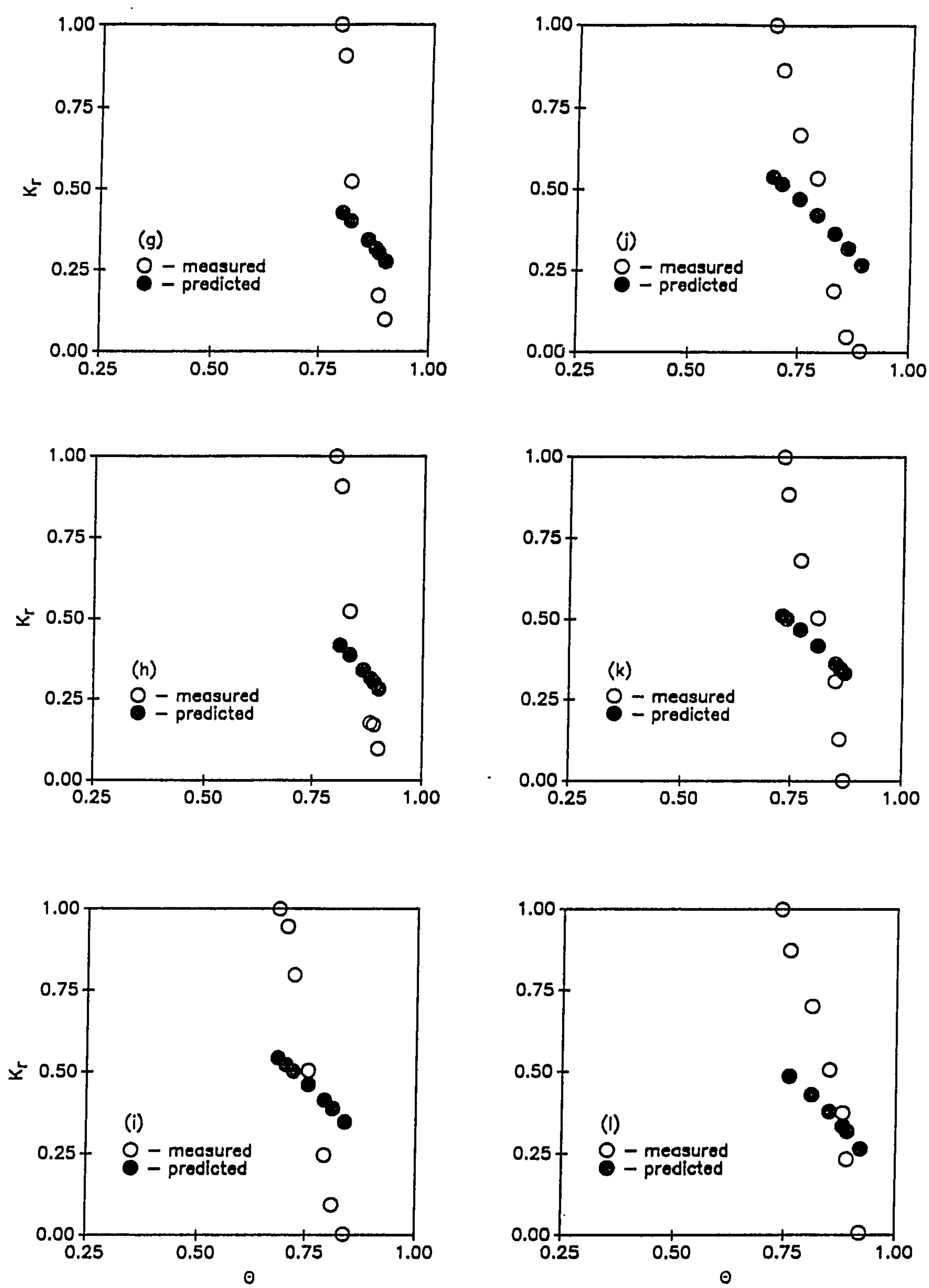

1.00
0.75
0.50
0.25
0.00
K_r
0.25
0.50
0.75
1.00
(a)
○ – measured
● – predicted
(d)
○ – measured
● – predicted
(b)
○ – measured
● – predicted
(e)
○ – measured
● – predicted
(c)
○ – measured
● – predicted
(f)
○ – measured
● – predicted
Θ

Figure 10. Measured air permeability (opened circles) and theoretical air permeability (soild circles) estimated from Eq. [14] for wheel trafficked soil samples


(g)
○ – measured
● – predicted
(j)
○ – measured
● – predicted
(h)
○ – measured
● – predicted
(k)
○ – measured
● – predicted
(i)
○ – measured
● – predicted
(l)
○ – measured
● – predicted
K_r
Θ
0.00
0.25
0.50
0.75
1.00

SUMMARY

Twelve undisturbed soil samples of Tama silty clay loam (fine-silty, mixed, mesic typic Argiudoll) were obtained from the surface A horizon of field plots. Samples were collected from the middle of wheel traffic and no-wheel traffic interrows. Air permeabilty of each sample was measured at selected soil matric potentials. A theoretical model relating air permeability to air filled porosity was developed.

The results of this study indicate that unsaturated hydraulic conductivity can be estimated reasonably well from air permeability data. The prediction of unsaturated hydraulic conductivity by this method was reliable over a range of bulk densities. The approach of using air permeability to predict unsaturated hydraulic conductivity is simple, convenient and promising.

Although the approach of using unsaturated air permeability to predict unsaturated hydraulic conductivity was accurate, one feature is in need of more understanding. The theoretical model describing air permeability as a function of air filled porosity did not always describe the observed air permeability values well. Further research to understand the shortcomings of this model and to develop and test additional models is needed.

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GENERAL SUMMARY

This study was presented in three papers. Paper I examined saturated hydraulic conductivity and chloride breakthrough in unoxidized and oxidized glacial till. Shelby tubes were used to collect undisturbed soil samples from depths of 2-12 m from several glacial till profiles. The Shelby tube samples studied were uniform in particle densities and in textural composition. Oxidized soil materials tended to have lower bulk density and higher saturated hydraulic conductivity than those of unoxidized soil materials. Saturated hydraulic conductivity decreased with depth down to about 9 m. Below this depth, conductivity was almost constant. Dispersivity increased slightly with depth.

Saturated hydraulic conductivity was one order of magnitude higher when measurements were conducted on the soil samples within Shelby tubes as compared with samples removed from Shelby tubes. In addition, early chloride breakthrough and significantly higher dispersivity for the samples within Shelby tubes confirmed the occurrence of side wall flow. Samples should be removed from Shelby tubes in order to achieve accurate measurements of conductivity and dispersivity.

Paper II of this study examined the effects of two tillage systems and traffic on soil water retention and soil water, chemical, and air transport. The results of this study showed that wheel traffic proved to be the dominant factor influencing the soil properties measured in this study. Bulk density increased significantly due to traffic in both no-till (NT) and chisel plow (CP) treatment.

The CP tillage, however, was more susceptible to wheel traffic compaction than NT. Tillage treatment did not influence bulk density significantly.

In general, soil water retention was influenced significantly by traffic. Tillage, however, showed no significant differences in the amount of water retained. Saturated hydraulic conductivity results were similar to that of bulk density in that only the traffic effect was significant. Unsaturated hydraulic conductivity, K(h), was increased by chiseling as compared to NT. However, this increase was not significant statistically. Traffic reduced unsaturated hydraulic conductivity for both tillages. This reduction was also not significant. Chloride breakthrough experiments revealed early initial breakthrough of chloride in all samples; indicating the occurrence of preferential flow. Initial breakthrough of chloride appeared earlier in CP than in NT regardless of the traffic treatment. Statistical analysis of variance for the hydrodynamic dispersion coefficient, D, and dispersivity, α, revealed nonsignificant effects for both tillage and traffic. Air permeability was increased by chiseling as compared to NT. This increase was not significant except at matric potential <-30 kPa. Traffic, however, reduced air permeability significantly for both tillages.

It can be inferred from this study that the effects of tillage and traffic for the properties measured were consistent. The increase in bulk density occurred primarily at the expense of larger pores. The shrinkage of the larger pores caused a decrease in saturated and unsaturated hydraulic conductivities and also a reduction in air permeabilities at every matric potential. Air permeability showed the greatest change of all properties measured.

Lack of statistical significance due to tillage may be a result of weed control cultivation which was performed a few weeks before collecting the soil samples. The relatively high coefficients of variation with the soil property measurements may necessitate more intensive sampling or perhaps larger sample sizes.

Paper III of this study presents a method in estimating unsaturated hydraulic conductivty from air permeability data. Twelve undisturbed soil samples of Tama silty clay loam (fine-silty, mixed, mesic typic Argiudoll) were obained from the surface A horizon of field plots. Samples were collected from the middle of wheel traffic and no-wheel traffic interrows. Air permeabilty of each sample was measured at selected soil matric potentials. A theoretical model relating air permeability to air filled porosity was developed. The model contains a parameter that can be used to predicte unsaturated hydraulic conductivity. The model parameter was determined for each soil samples by curve fitting the model to the measured air permeability data. The model parameter for each sample was then used to predict unsaturated hydraulic conductivity for each sample. Predicted unsaturated hydraulic conductivity was compared to measured unsaturated hydraulic conductivity. The results of this study indicate that unsaturated hydraulic conductivity can be estimated reasonably well from air permeability data. The approach of using air permeability to predict unsaturated hydraulic conductivity is simple, convenient and promising.

Although the approach of using unsaturated air permeability to predict unsaturated hydraulic conductivity was accurate, one feature is in need of more understanding. The theoretical model describing air permeability as a function of air filled porosity did not always describe the observed air permeability values well. Further research to understand the shortcomings of the model and to develop and test additional models is needed.

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